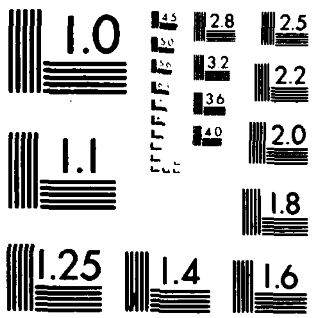
AD-A089 621 NEW MEXICO UNIV ALBUQUERQUE DEPT OF GEOLOGY F/G 8/13
PROPERTIES AND PREDICTION OF CALICHE IN ALLUVIAL BASINS OF THE --ETC(U)
JUL 80 S G WELLS, J D SCHULTZ AFOSR-78-3572
UNCLASSIFIED AFOSR-TR-80-0747 NL

1 of 2




MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

AFOSR-TR- 80-0747

LEVEL II

2

AD A089621

DTIC
ELECTE
SEP 26 1980
D
C

DDC FILE COPY

Approved for public release;
distribution unlimited.

80 9 25 071

UNCLASSIFIED

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER AFOSR-TR- 80-0747 | 2. GOVT ACCESSION NO. AD-A089 621 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) PROPERTIES AND PREDICTION OF CALICHE IN ALLUVIAL BASINS OF THE SOUTHWESTERN UNITED STATES | | 5. TYPE OF REPORT & PERIOD COVERED Final 1 Mar 78 - 31 Mar 79 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Stephen G Wells, Jerald D Schultz | | 8. CONTRACT OR GRANT NUMBER(s) AFOSR 78-3572 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Geology, University of New Mexico, Albuquerque, NM 87131 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2309/D9 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NP, Bolling AFB, Bldg. #410, Wash DC 20332 | | 12. REPORT DATE July 1980 |
| | | 13. NUMBER OF PAGES 171 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release;
distribution unlimited.

17. DISTRIBUTION ST. ENT (of abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY TES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Four major study areas were selected to carry out detailed field and laboratory investigations of calcium carbonate cementation. These four study areas include: (1) selected alluvial basins in the southern Basin and Range Province of Arizona; major characteristics include low-carbonate parent material, open but poorly integrated basins, tectonic stability, areas of active aggradation, and wide variations in alluvium texture; (2) selected alluvial basins along the Colorado River in western Arizona; major characteristics include high-carbonate parent material, open drainage basins, active dissection, and coarse-grained

(Cont)

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AD A089 621

UNCLASSIFIED

alluvium; (3) the Las Vegas alluvial basins in southern Nevada major characteristics include high-carbonate parent material, numerous geomorphic surface, open and closed drainage basins, and variable textures of alluvium; and (4) selected basins in central Nevada major characteristics include variable carbonate content in parent materials, tectonically active, closed and open basins, and variable textures of parent materials.

(3)

AFOSR-TR-80-0747

AFOSR-78-3572

# PROPERTIES AND PREDICTION OF CALICHE IN ALLUVIAL BASINS OF THE SOUTHWESTERN UNITED STATES

Applied to Siting and Engineering of the Multiple Aim Point Missile System

by


Stephen G. Wells
~~Principal Investigator~~

~~and~~

Jerald D. Schultz
~~Research Assistant~~




FINAL REPORT, 1 Mar 7? - 31 Mar 79

submitted to

(16) 239

Air Force Office of Scientific Research

(17) 01

Air Force Systems Command, USAF

Bolling Air Force Base, DC 20332

(12) 174

July 1980

394 1-- B

## ABSTRACT

Alluvial basins in the southwestern United States are being assessed for siting of the Multiple Aim Point Missile System (MX). Accumulation of calcium carbonate (caliche) in the upper horizons portion of the basin fill is a secondary alteration due to pedogenic process. Caliche development in alluvial materials change the physical and chemical properties of the in-situ material. Specifically, calcium carbonate cementation binds clastic material into large grain sizes, increases compressive strength of the material increases the bulk density, and reduces the infiltration rate of downward percolating waters. Consequently, these changes in engineering characterisics may pose a potential hazard to the construction and survivability of the MX system. These properties of alluvium changes with increasing calcium carbonate content which increases with time.

Detailed field investigations, mapping from aerial photography, laboratory experiments and petrographi-chemical analyses were con-ducted on caliches sampled in Arizona, Nevada and California. Based on these investigations several qualitative and quantitative methods of predicting caliche occurrence and degree of development were devised. Field and map criteria as well as satellite-imagery analyses can be used to predict caliche occurrences in alluvial basins. Regions in alluvial basin which have the following characteristics are most likely to have well-indurated and thick caliche: (a) old alluvial material composed of carbonate and/or basic igneous clasts, (b) alluvium downwind from playas which have

concentrations of calcium (c)material that is coarse grained and poorly sorted, and (d) older geomorphic landscape surfaces. Areas least likely to have appreciable amounts of $CaCO_3$ cementation may be fine-grained sediments composed of acid igneous rocks and areas of young geomorphic surfaces.

In certain portions of alluvial basins, erosion has removed most of the upper soil horizons and exposed the caliche to the near surface. Satellite imagery (Landsat) is useful for detecting the caliche by variations in image density and morphology for the landscape. Caliche reduces the erodibility of the landscape which causes (a) a decrease in the number of drainage lines per unit area (b) preservation of multiple geomorphic surfaces, and (c) modification of channel characteristics.

## ACKNOWLEDGEMENTS

The author expresses his sincere thanks to the Facility Survivability Branch, Civil Engineering Research Dividision of the Air Force Weapons Lab, KAFB for providing facilities and assistance, and for the interest given to my work. Special thanks is given to Lt. Col. F. Leech of the Civil Engineering Research Division for his sincere cooperation. This study benefited from discussions and time shared with Dr. J. Hawley, Dr. L. Lattman, Capt. M. Yeager, Capt. L. Karably, Mr. S. Melzer, Lt. Col. J. Neal, and Lt. J. Shinn. The author expresses his sincere thanks to Capt. A. Schenker for suggesting the project and for his time and ideas related to this research and to Jerry Schultz for his extreme help in the field nd laboratory. Mr. J. Husler is thanked for his contribution with the chemical studies. The author is grateful to the Air Force Systems Command for support of this research.

TABLE OF CONTENTS

## APPENDICES

LIST OF FIGURES

## LIST OF TABLES

## LIST OF PLATES

## 1. INTRODUCTION

The Basin and Range Province of the Western Unnited States is being assessed for the siting of the Multiple Aim Point Missile System (MX System) (Fig. 1). This physiographic province is characterized by fault-block mountain ranges and intervening alluvial basins (Fig. 2). Gently-sloping alluvial plains between these bedrock ranges are the primary sites for the MX Systems. The geology of these alluvial basins must be delineated if effective siting of the MX Systems is to occur. Specifically, surficial conditions and processes of potential basin sites may pose hazards to the survivability of the MX Systems and may cause difficulty in the construction of the missile sites (Wells, 1977).

The accumulation of secondary calcium carbonate, referred to as caliche, in alluvial fill is a common phenomena in the desert basins of the Basin and Range Province. This calcium carbonate may occur as interstitial fillings in basin sedimentary fill or surface coatings of aggregates of the clastic fill. Cementation by calcium carbonate will alter the chemical and physical properties of the original sedimentary fill. Secondary calcium carbonate cementation increases the strength and density of previously unconsolidated ill by binding clasts into larger particles. Wells (1977) demonstrated that optimum siting of MX Systems depends upon an evaluation of the types and distribution of secondary calcium carbonate in the alluvial basins.

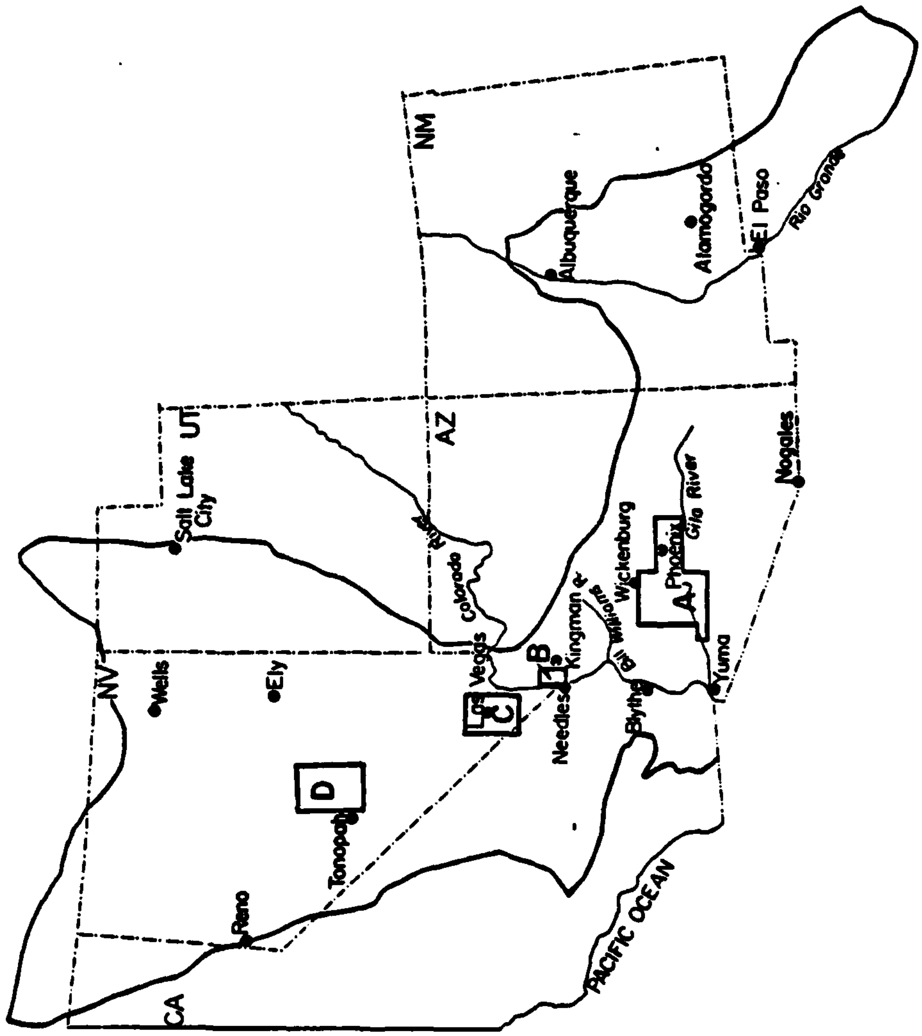



Figure 1. Map of the Basin and Range Province in western United States showing boundaries, major cities, major drainages and field study sites. Study sites A, B, C and D represent regions of detailed field investigations conducted during this investigation.

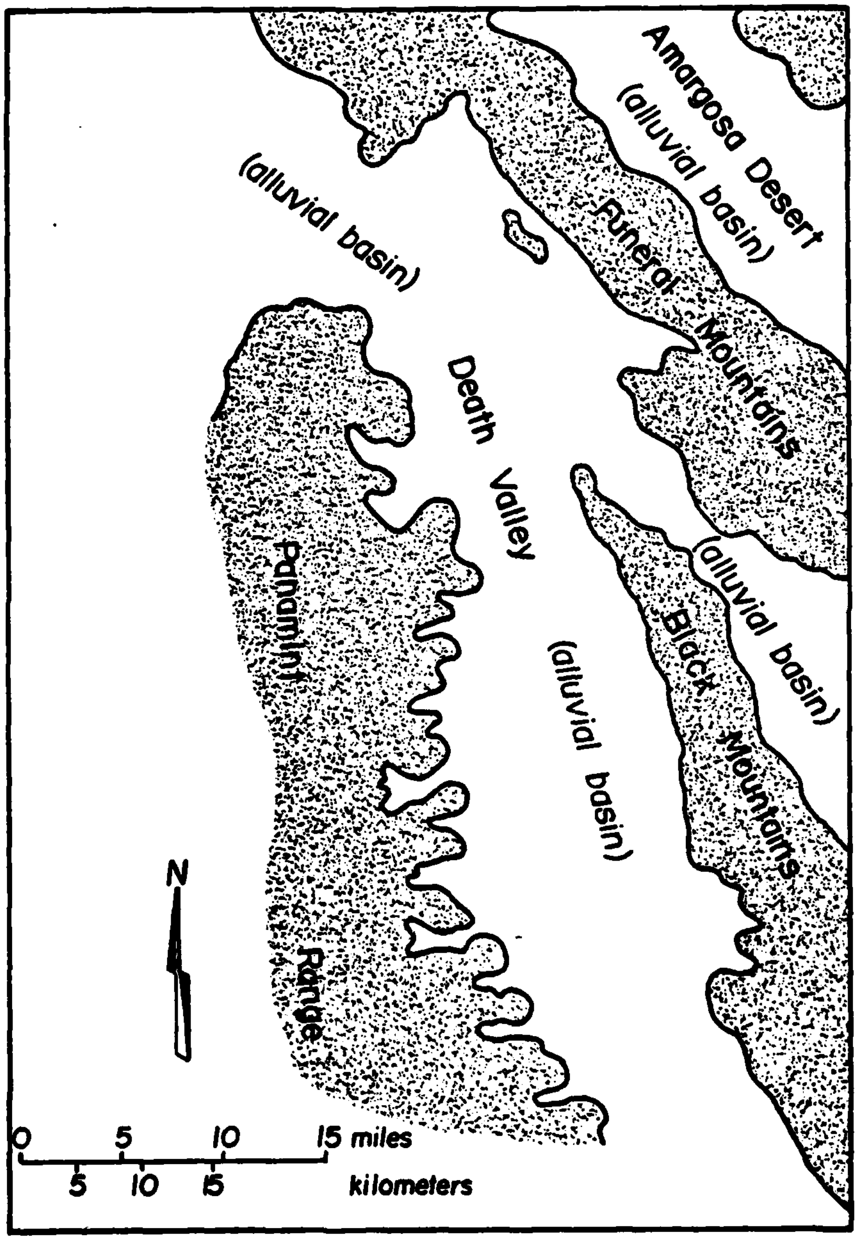



Figure 2. Generalized map of Death Valley area in Basin and Range illustrating alternating mountains and alluvial valleys.

## Research Objectives

The major objectives of this study are detailed below:

1) To determine the types of caliche that will affect the survivability and engineering aspects of the MX Systems;
2) To review and delineate the general chemical and physical properties of secondary calcium carbonate cementation in the Basin And Range Province of the western United States relevant to MX Systems siting and engineering.
3) To determine those major variables which influence the occurrence and regional distribution of calcium carbonate cementation, in alluvial basins.
4) And, to delineate regions within selected portions of the Basin and Range which contain well-developed and extensive deposits of secondary calcium carbonate.

## General Research Procedures

This investigation utilizes published data on secondary calcium carbonate in desert basins. Data derived from the published literature compliments the laboratory and field studies conducted during this research project. Specifically, the published literature provides data on: (1) types of secondary calcium carbonate deposits, (2) properties of these deposits, and (3) known occurrences of calcium carbonate deposits in the Basin and Range Province.

Field investigations provided data on the characteristics and distribution of secondary calcium carbonate cementation. In addition, field studies provided checks for predictive techniques developed during this investigation. Observations, measurements and sample collections of carbonate cementation occurred in four basic study areas (Fig. 1). In each study area the following conditions were recorded:

1) major morphologic parameters of the cemented alluvium;
2) major characteristics of cemented alluvium; and,
3) landscape characteristics overlying the cemented alluvium

Calcium carbonate accumulations in soil horizons were described according to methods outlined by Birkeland (1974) and include: (1) horizon thickness (2) texture, (3) stage of accumulation, and (4) degree of cementation. Soil maps provided by the Soil Conservation Service were used in conjunction with field studies. Measurements and descriptions of the parent material included clast lithology and textural parameters, especially grain size. Results of these studies are summarized in the Appendixes.

Methods of characterizing the landscape features were based on methods developed by Wells (1976). Measurements included: (1) slope measurements with transit and stadia rod, (2) microrelief measurements, (3) desert pavement and varnish development, and (4) estimates of the degree of dissection.

Laboratory investigations included: (1) petrographic analysis of calcium carbonate samples, (2) chemical analyses of calcium carbonate cement, (3) controlled weathering experiments, (4) mapping landscape features and alluvial fill from aerial photography and imagery, and (5) quantitatively analyzing satellite imagery for differentiating areas of cementation. Results of petrographic and chemical analyses are given in the Appendixes. Chemical analyses were conducted by the staff chemist, John Husler. Detailed laboratory procedures used in the weathering experiments are given in Appendix B. Procedures utilized in the satellite imagery studies included the measurement of imagery density on positive, Landsat transparencies with MacBeth Transmission Desitometers (TD-504).

Study Areas

Four major study areas were selected to carry out detailed field and laboratory investigations of calcium carbonate cementation. These four study areas are given in Figure 1 and include:

1) Study Area A: selected alluvial basins in the southern Basin and Rangne Province of Arizona; major characteristics include low-carbonate parent material, open but poorly integrated basins, tectonic stability, areas of active aggradation, and wide variations in alluvium texture.
2) Study Area B: selected alluvial basins along the Colorado River in western Arizona; major characteristics include low-carbonate parent material, open drainage basins, active dissection, and coarse-grained alluvium.

3) Study Area C: the Las Vegas alluvial basins in southern Nevada; major characteristics include high-carbonate parent material, numerous geomorphic surface, open and closed drainage basins, and variable textures of alluvium.

4) Study Area D: selected basins in central Nevada; major characteristics include variable carbonate content in parent materials, tectonically active, closed and open basins, and variable textures of parent materials.

Selected sample stations in these study areas are given in Appendix A.

## 2. APPLICATION OF CALICHE PROPERTIES AND DISTRIBUTION TO MULTIPLE AIM POINT MISSILE SYSTEMS

Cementation of alluvial basin fill by calcium carbonate affects siting of MX Systems in two major ways: (1) on nuclear weapons effects (NWE) and (2) on construction of facilities. Since alluvial basins of the Basin and Range Province are so varied in the types and sizes of sediments filling them, predicting the occurrence of calcium carbonate cementation and subsequent understanding of the cemented alluvium response to a NWE environment will greatly enhance the survivability of a MX System.

### Nuclear Weapons Effects

Secondary calcium carbonate occurrence, areal extent and distribution with depth will aid in predicting; (1) crater size, (2) amount and size of ejecta, and (3) the shock propagation that radiates out from the detonation point. All three effects need to be better understood when designing the MX Systems to a stated level of survivability. For example, loose, uncemented alluvium yields relatively larger crater regions than well-indurated alluvium. Calcium carbonate cemented alluvium produces a competent media for cratering which results in reduced ejecta. However, massive cementation also influences the size of ejecta that will occur. Loose, minimally indurated alluvium will produce ejecta no larger than the in-situ size materials. With calcium carbonate cementing the alluvium, ejecta size increases dramatically, especially well-indurated alluvium which approaches concrete conditions.

A buried, cemented layer under loose alluvium acts differently than would a massively cemented section as described previously. A buried massively cemented alluvial layer will influence the aspect ration (Ra/Da, ratio of apparent crater radius/depth of apparent crater) of cratering when it imposes an impedance mismatch between the loose alluvium and cemented alluvium interface. If unconsolidated alluvium overlies massivley cemented zone, the cratering mechanism will tend to bottom out at the resistant layer, and the aspect ratio may be expected to increase with a corresponding increase in the amount of ejecta.

Another NWE consideration is that of attenuation of ground shock propagation. In loose medium, the bulk density is low, as compared with highly indurated alluvium. As the overall denisyt and competency of the alluvium increases with cementation so does ts ability to transmit strong motion seismic shock waves to greater distances. Peak Particle velocity, scaled peak displacement and scaled peak acceleration may all be expected to be higher for indurated alluvium than uncemented material (Crawford et al, 1974). Depending on the types of seismic signal that may be propagated through the cemented alluvium, a strategic facility will need to be designed to survive varying degrees and modes of seismic wave velocity acceleration, frequency, and amplitude.

## Construction of MX System Facilities

In addition to the NWE concerns, the engineering properties of alluvium altered by cementation is important to facility construction. The initial cost of constructing an MX System facility will depend to a large extent on the ease of excavation for a foundation or in case of the trench concept a 4 m wide by 6 m deep x 18 km trench. Calcium carbonate cementation of alluvium will make excavation more difficult and time consuming. These conditions will increase the cost of MX
System facilities.

Once the facility is built there will be an overburden of unconsolicated material (∿ ½ m thick). If an area has extensive in-situ cementation then there is reason to be concerned that the overburden covering the structure will undergo re-cementation. This could degrade the egress ability of the missile (the missile container must break through the roof of the tunnel and overburden for egress) in that a cemented overburden would be more difficult to escape through than loose backfill.

Calcium carbonate cementation of the alluvium will also influence the hazards of flooding to the MX System facilites. Loose alluvium allows rapid infiltrate surface water while alluvium that has been cemented will resist infiltration and will increase the potential for flooding. Therfore where cementation is prevelant, flood waters can be channeled far down the desert slopes and endanger a structure housing strategic missiles. For the most part, secondary calcium carbonate cementation of alluvium can only complicate the problems associated with MX System structures.

## 3. TYPES AND ORIGINS OF SECONDARY CALCIUM CARBONATE CEMENTATION IN ALLUVIAL BASINS

### Classification

A variety of surface and subsurface hydrogeologic conditions result in the precipitation of calcium carbonate over individual olasts or over clast aggregates in the alluvial fill. The diversity in the conditions under which calcium carbonate is deposited creates difficulty in classifying caliche types. In addition, the classification systems are based on the genetic conditions, morphologic parameters or the content of calcium carbonate.

In this investigation, the major types of caliche in the Basin and Range Province of the southwestern United States are classified as either pedogenic or nonpedogenic (Table 1). This genetic classification can be subdivided further by specifying (1) the degree of

Table 1. General classification of caliche deposits in alluvial fill of basins in the western United States (after Carlisle, 1978).

| CATEGORY | PROCESS |
|---|---|
| Pedogenic Caliche | Authigenic cement has been concentrated vertically within a soil profile. |
| Nonpedogenic Caliche | Authigenic cement has been intoduced into host soil or sediment by nonsoil-forming processes:<br><br>- groundwater caliches<br>- spring caliches<br>- fluvial caliches<br>- lacustrine caliches |

pedogenic cementation or (2) the environment in which the non-pedogenic calcium carbonate was deposited (Fig. 3). These major nonpedogenic environments include groundwater, springs streams and lakes. Caliche formed by pedogenic processes and in groundwater environments occur as interstitial fillings in the alluvial; whereas, caliche deposited in spring, lacustrine or fluvial environments commonly coat the land surface on the alluvial fill. Of all these genetic types, pedogenic calcium carbonate cementation is the most regionally extensive. Other types of caliche are controlled by local hydrologic and geologic conditions. Thus, the present study focused on the pedogenic form of calcium carbonate.

Six major types of secondary calcium carbonate cementation are described by Lattman (1973, 1975) and are adopted for use in this study. These caliche types are differentiated on the basis of variations in morphology, physical properties, vertical and lateral extent which are all important parameters related to MX siting. Variations in chemical constituents are not condsidered to be important for caliche classification; however, varying concentrations of calcium carbonate affect the properties of caliche.

Detailed descriptions of these caliche types are given by Cooley et al (1973):

1) "Caliche: Caliche is used to encompass all secondary deposits of calcium carbonate although this term has been commonly used to designate deposits of calcium carbonate by pedogenic processes. However, caliches of pedogenic origin are transitional with caliches of nonpedogenic origin.

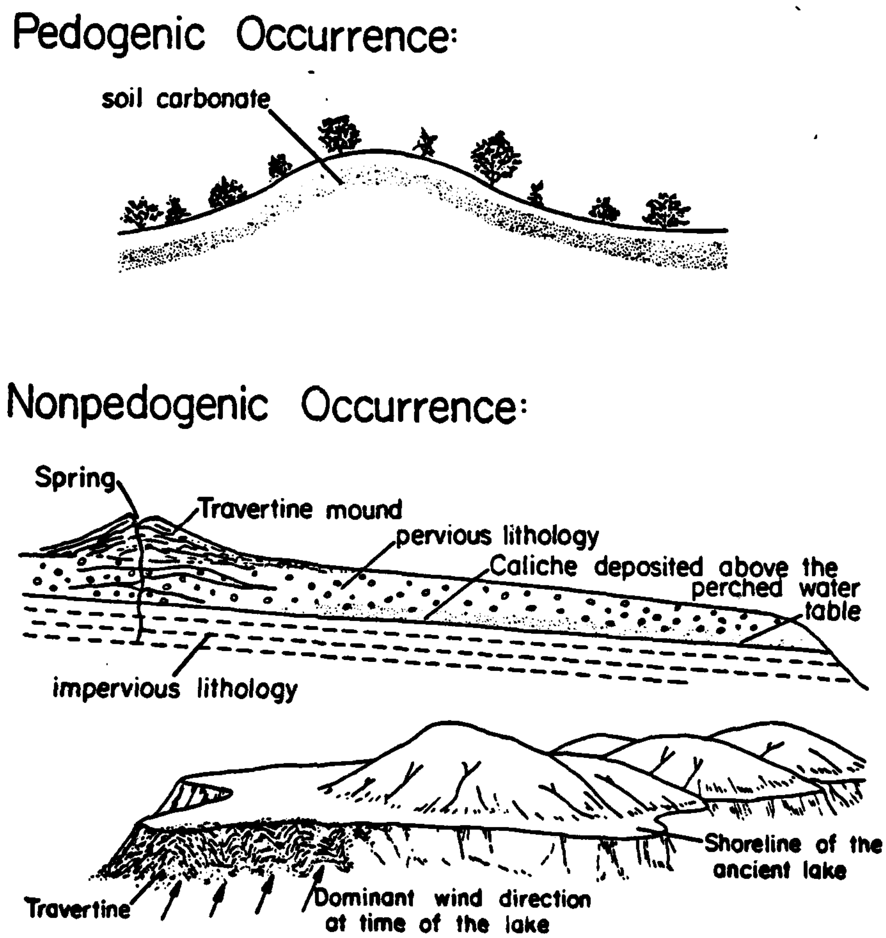



Figure 3. Diagrammatic sketch of major types of caliche deposits in alluvial valleys of Basin and Range (after Hunt, 1974).

Thus, it is recommended that caliche be used as a general term for all secondary calcium carbonate deposits.

2) Pedogenic Caliche: Pedogenic caliche is an accumulation of secondary calcium carbonate formed by soil related processes and consists of two major transitional types depending on thickness and amount of calcium carbonate.

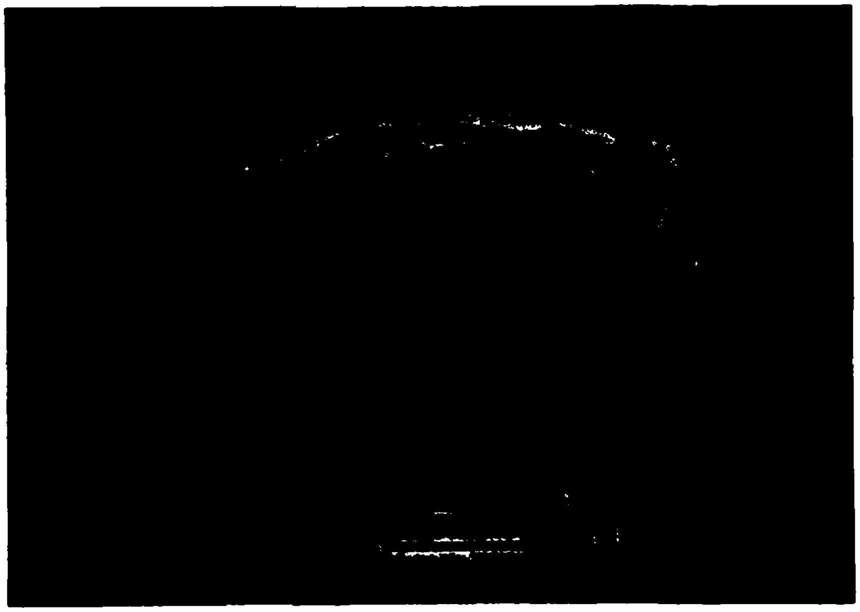
   (a) Calcic horizon is a soil horizon of calcium carbonate accumulation which is more than 15 cm thick, has a calcium carbonate equivalent content of more than 15 percent (by weight), and has at least 5 percent (by volume) of identifiable secondary carbonates (Soil Survey Staff, 1967).

   (b) Petrocalcic horizon is a laterally continuous, cemented or indurated horizon (Fig. 4). Dry fragments of caliche do not slake in water and noncapillary pores are plugged (Soil Survey Staff, 1967). This horizon may be capped by a laminar layer. This horizon is often called calcrete. Calcrete terminology is discussed by Carlisle (1978).

3) Laminar Layer: This layer consists of thinly laminated calcium carbonate and contains few or no coarse clasts (Fig. 4). Laminar layers are found under a variety of conditions. They may occur as a more or less continuous cap on a petrocalcic horizon where it is a late stage feature of soil formation (Gile *et al*, 1965). They may also occur on any relatively impermeable surface such as bedrock or

Figure 4a. Petrocalcic caliche showing clasts suspended in carbonate matrix.

Figure 4b. Laminar layers resting on petrocalcic horizon.



clay. Laminar layers are relatively impermeabiltiy.

4) Gully-Bed Cementation: Gully-bed cementation is a massive, generally nonlaminated, well cemented layer. It is found on, or immediately beneath, the bed of desert streams. It is of low permeability and commonly includes boulders, pebbles, and sand that were earlier bedload. Such layers are discontinyous laterally but other wise may be indistinguishable from petrocalcic horizons.

5) Case Hardening: Case hardening is cementation of alluvial and colluvial material exposed in very steep to vertical slopes, such as gully sides and terrace risers (Fig. 5). It forms by thin-film surface water which causes solution of silt-sized calcareous material and redeposition. It is locally well indurated, depending upon age and sorting of the cemented material. Older exposures are better cemented, and in any one exposure the poorer the sorting (the greater the range in grain size) the better the cementation.

6) Caliche Rubble: Caliche rubble connsists of loose, generally irregular pieces of calcium carbonate lying loose on the land surface (Fig. 5). It forms by the mechanical breakup of laminar layers and near surface petrocalcic horizons and by seperation of coating from pebbles and larger clasts.

These six types of caliche are ranked according to selected characteristics given in Table 2. These characteristics include: (1) areal extent or distribution in an alluvial basin, (2) relative

Figure 5a. Case-hardening of alluvium exposed in bank of desert wash.

Figure 5b. Caliche rubble on alluvial fan surface.

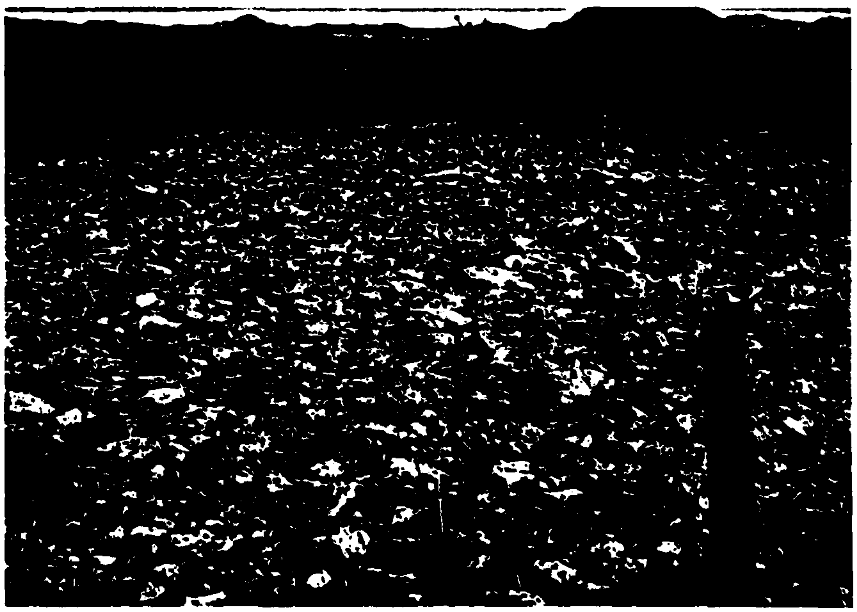


Table 2. Types of characteristics of secondary carbonate cementation and ranking of types according to spatial characteristics.

| Type | Origin | RANKING Areal Extent | Relative Thickness | Areal Continuity | Depth Below Surface |
|---|---|---|---|---|---|
| Calcic Horizon (ca) | Pedogenic | 1 | 1 | 1 | 1 |
| Petrocalcic Horizon (pca) | Pedogenic | 2 | 3 | 2 | 2 |
| Gully-Bed Cementation (gbc) | Nonpedogenic | 4 | 4 | 5 | 4 |
| Case-Hardening (ch) | Nonpedogenic | 3 | 2 | 3 | 5 |
| Laminar Layer (ll) | Pedogenic/Nonpedogenic | V | 6 | 4 | 3 |
| Caliche Rubble (cr) | Nonpedogenic | V | 5 | NA | 6 |

V = highly variable  NA = not applicable  1 - represents greatest
6 - represents least

This table is generalized and regionally representative of caliche in the southwestern United States; ranking may change at a given site.

thickness compared to other types, (3) lateral continuity of caliche horizon, and (4) depth to the top of the caliche horizon below the surface. The ranking is designed such that 1 represents caliches with the greatest areal extent, thickness, etc. and 6 represent caliches with the least values. Of these six types, calcic and petrocalcic horizons are the most significant, and both form by pedogenic processes. That is, calcic and petrocalcic horizons have the highest ranking in the four characteristics, and more importantly, are the most continuous caliches in alluvial basins of the southwestern United States (Fig. 6). Gully-bed cementation and laminar layers are discontinous although they occur widely over alluvial basins.

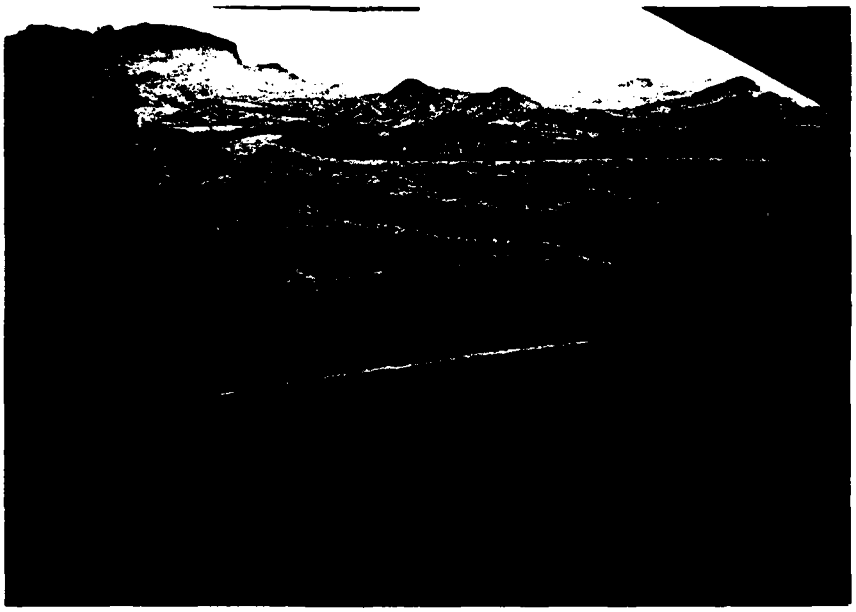
Gile _et al_ (1966) present a classification scheme that is regional only includes pedogenic caliche. Many aspects of Gile's classification scheme are adopted in the present study and will be discussed later. Reeves (1976) offers a well-summarized description of other ways to classify caliche than the ones given above. The classifications discussed by Reeves are concerned primarily with describing local morphologic characteristics rather than regional parameters.

## Criteria for Recognizing Pedogenic Caliche

Gile and Grossman (1979) list five field characteristics to distinguish calcium carbonate horizons of pedologic origin:

1) caliche horizons approximately paralle the soil surface;
2) caliche horizons usually range from a few cm to tens of cm below the land surface, and are within reach of wetting by infiltration;

Figure 6. Extensive petrocalcic horizon exposed over entire alluvial fan surface.



3) horizons have distinctive morphologies that are differ from surrounding horizons;

4) caliche horizons form in a morphologic sequence related to time;

5) Depth of pedogenic horizon changes with the smount of precipitation, and this indicates an illuvial-eluvial relationship.

In addition, morphologic features of hand specimens are useful and will be discussed in section 4 of this report. Distinquishing caliche types (nonpedologic vs pedologic) by chemical analysis is difficult and is not utilized in this study.

Origin of Calcium in Pedogenic Caliche

Sources of calcium in cemented soil horizons of desert alluvial valleys are numerous. Major sources include the weathering of bedrock in mountainous areas, weathering of the parent material in alluvium, reworking from precipitated calcium in groundwater zones, and input from the wind and rainfall. Calcium source-areas can be classified into three major types: (1) bedrock, (2) alluvial fill and (3) atmospheric. Processes operating in these areas which tend to bring calcium to the soil horizon are illustrated in Figure 7. In addition to these major sources, older deposits of secondary calcium carbonate serve as sources for younger caliche horizons.

Two predominant sources of calcium in pedogenic horizons are weathering of parent material and atmospheric contributions (Gile and Grossman, 1979; Yaalon and Ganor, 1973). Alluvium is the parent

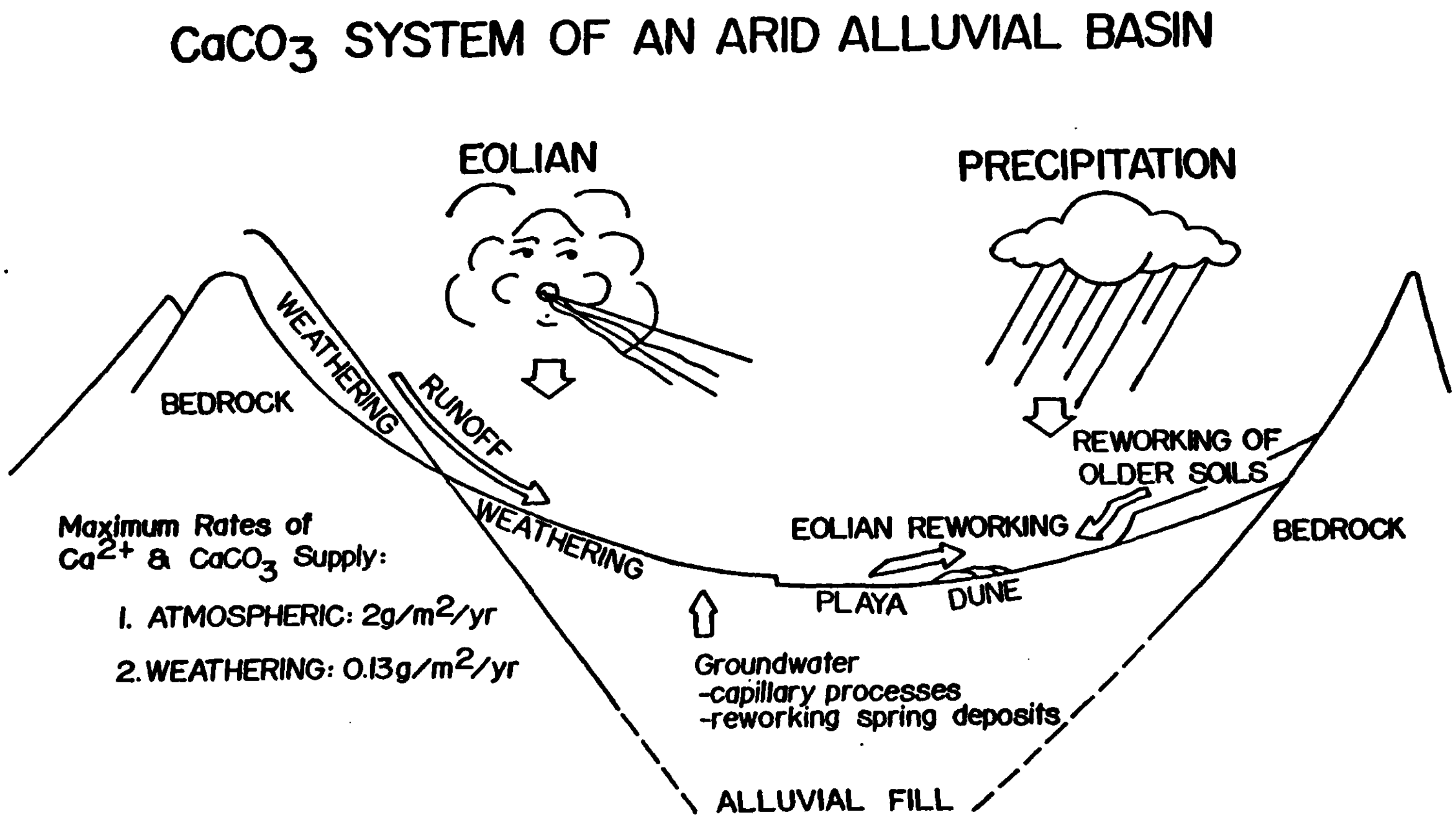



Figure 7. Diagrammatic sketch of desert basin and sources of $Ca^{2+}$ or $CaCO_3$ for pedogenic caliche.

material in the desert valleys of the southwestern United States. Eolian transport of dry dust and precipitation of dissolved calcium add calcium thay may be derived outside the boundaries of the desert valleys. Thus, these two sources can be considered as external (atmospheric) or internal (parent material) with respect to the confines of the desert basin.

External Contributions:

The amount of calcium carbonate in eolian dust is given for selected western states in Table 3. The amount of calcium added to the land surface by eolian dust was studied by Gile and Grossman (1979). The range for eolian contributions is from 0.4 to 1.3 $g/m^2/yr$. Deposition of this calcium by dust is relatively uniform over the land surface (Gile and Grossman, 1979). In addition to dust, precipitation adds dissolved calcium to the soil horizon. Rainfall also wets the dust on the land surface dissolving calcium and supplying calcium to the subsurface. Concentrations of calcium in rain water is between 3 and 4 mg/l in the southwestern United States (Junge and Werby, 1958). Gile and Grossman (1979) determined that calcium added by the mean annual precipitation in an arid region would form 1.5 $g/m^2/yr$ of calcium carbonate. An average contribution of both dust and rainfall derived calcium carbonate is approximately 2 $g/m^2/yr$. Estimates of calcium carbonate accumulation determined by the amount of carbonate in selected soil profiles and soil age gives a range of 0.1 to 1.0 $g/m^2/yr$ (Table 4) (Gile and Grossman, 1979). These long term rates of accumulation range between 2 and 3 $g/m^2/yr$ and are similar to the values measured in the field.

Table 3. Calcium carbonate percentages of eolian dust in selected western states.

| LOCATION | PERCENT $CaCO_3$ | REFERENCE |
|---|---|---|
| Texas | 5 to 20 | Warn & Cox, 1951 |
| Kansas | Up to 6 | Swineford & Frye, 1951 |
| Nevada | 25 to 27 | Kaplan, 1973 |

Table 4. Amount and rate of pedogenic carbonate accumulation grouped by soil age.

| Epoch | Estimated range in age | Range in carbonate as $CaCO_3$ Total | Range in carbonate as $CaCO_3$ Accumulation rate |
|---|---|---|---|
| | kyrs | $g/m^2$ | $g/m^2/yr$ |
| Holocene | 1-4 | 5-12 | 1-12 |
| | 2-4 | 8-20 | 2-10 |
| Latest Pleistocene | 8-15 | 46 | 3-6 |
| Latest Pleistocene | 8-15 | 22-75 | 1-9 |
| | 25-75 | 140-260 | 2-10 |
| Late Pleistocene | 25-75 | 213-300 | 3-12 |
| Late mid-Pleistocene (youngest) | 200-300 | 751-834 | 2-4 |
| Late mid-Pleistocene (oldest) | 300-400 | 795-1090 | 2-3 |
| Mid-Pleistocene (youngest) | 400-500 | 1200-1370 | 2-3 |
| Mid-Pleistocene (oldest) | >500 | 1380-1840 | 2-3 |

Internal Contributions:

The lithology of the clasts in the basin fill influences the amount of calcium contributed to the soil horizon. The bedrock in the mountain ranges surrounding the alluvial valley is the ultimate parent material for the alluvial fill. Ruhe (1967) demonstrated relationships between the mountain bedrock lithology and the concentration of lithologies in the alluvial fill flanking the mountain. Parent materials with high concentrations of calcium develop thicker caliche horizons faster than those with lower calcium content (Gile and Grossman, 1979). Thus, mountain ranges composed of limestones and dolomites shed high-calcium parent material into the valleys and such areas have thick, indurated calcium carbonate horizons in the soil zone.

Areas such as the Las Vegas, Nevada basin (study area C) have extensive outcrops of Paleozoic carbonates (Table 5). Consequently, massive caliche horizons occur in the alluvial fill of this area. Study areas in southwestern Arizona are characterized by massive caliche horizons yet little carbonate lithologies occur in the mountain ranges. In Arizona the mountain ranges and parent material are dominantly igneous rocks (Table 5). Calcium carbonate in the soils must be derived from the atmosphere or from the weathering of the small amount of calcium from minerals in the igneous parent material. In order to determine the relative contribution of calcium by the weathering of igneous rocks versus contributions by the atmosphere, an experiment was designed to measure the amount of calcium released from acid and basic igneous rocks under simulated

Table 5. Planimetric areas of bedrock lithologies in mountain ranges and isolated outcrops, Basin and Range Province.

ARIZONA

| Lithology in Contributing Mountain Ranges | Surface Area ($km^2$) | Percent Surface Area |
|---|---|---|
| Acid Igneous | 464.8 | 9 |
| Basic Igneous | 2616.3 | 52 |
| Metamorphic | 1552.0 | 31 |
| Clastic Sedimentary | 368.2 | 7 |
| Carbonate Sedimentary | 60.9 | 1 |
| TOTAL: | 5062.2 | 100 |

NEVADA

| | | |
|---|---|---|
| Acid Igneous | 5694.1 | 67 |
| Basic Igneous | 392.8 | 5 |
| Metamorphic | 498.6 | 6 |
| Clastic Sedimentary | 730.3 | 9 |
| Carbonate Sedimentary | 1061.6 | 13 |
| TOTAL: | 8377.3 | 100 |

weathering conditions. Experimental design, procedures and results are given in Appendix B. Table 6 summarizes the major findings of the experiment. There was no apparent leaching of calcium or magnesium from the acid igneous rock (granite). However, the basic igneous rock (basalt) yielded approximately 0.13 $g/m^2/yr$ of calcium and 0.06 $g/m^2/yr$ of magnesium. It must be noted that these weathering values represent extreme weathering conditions which are not common to deserts. Additional evidence indicating that basic igneous rocks yield small quantities calcium by weathering is given by Kaplan (1973) (Fig. 8). Increased weathering of both bedrock outcrops and clasts of basalt show successive decreases in CaO content (percent by weight). It would appear that the large outcrops of basic igneous rocks in the southern Arizona study area could provide limited quantities calcium for caliche develepement (Table 5).

A comparison of calcium supply from the weathering of non-carbonate parent material and from the input of the atmosphere is given in Figure 7. Under extreme weathering conditions simulated in the lab, weathering only supplies 1/20 of the calcium that is supplied by eolian and rainfall sources. It is apparent from this study that atmospheric contributions of calcium is the predominant source. Although other sources locally may supply excessive calcium, the wind and rainfall supply a relatively uniform amount over an area.

Table 6. Amounts of calcium and magnesium leached from basalt and granite during weathering experiment.

| | Basalt | Granite | Basalt | Granite |
|---|---|---|---|---|
| Calcium | 0.0357 $\frac{mg/cm^2}{day}$ | No apparent leaching | .1285 $\frac{grams/meter^2}{year}$ | No apparent leaching |
| Magnesium | 0.0179 $\frac{mg/cm^2}{day}$ | No apparent leaching | .0644 $\frac{grams/meter^2}{year}$ | No apparent leaching |

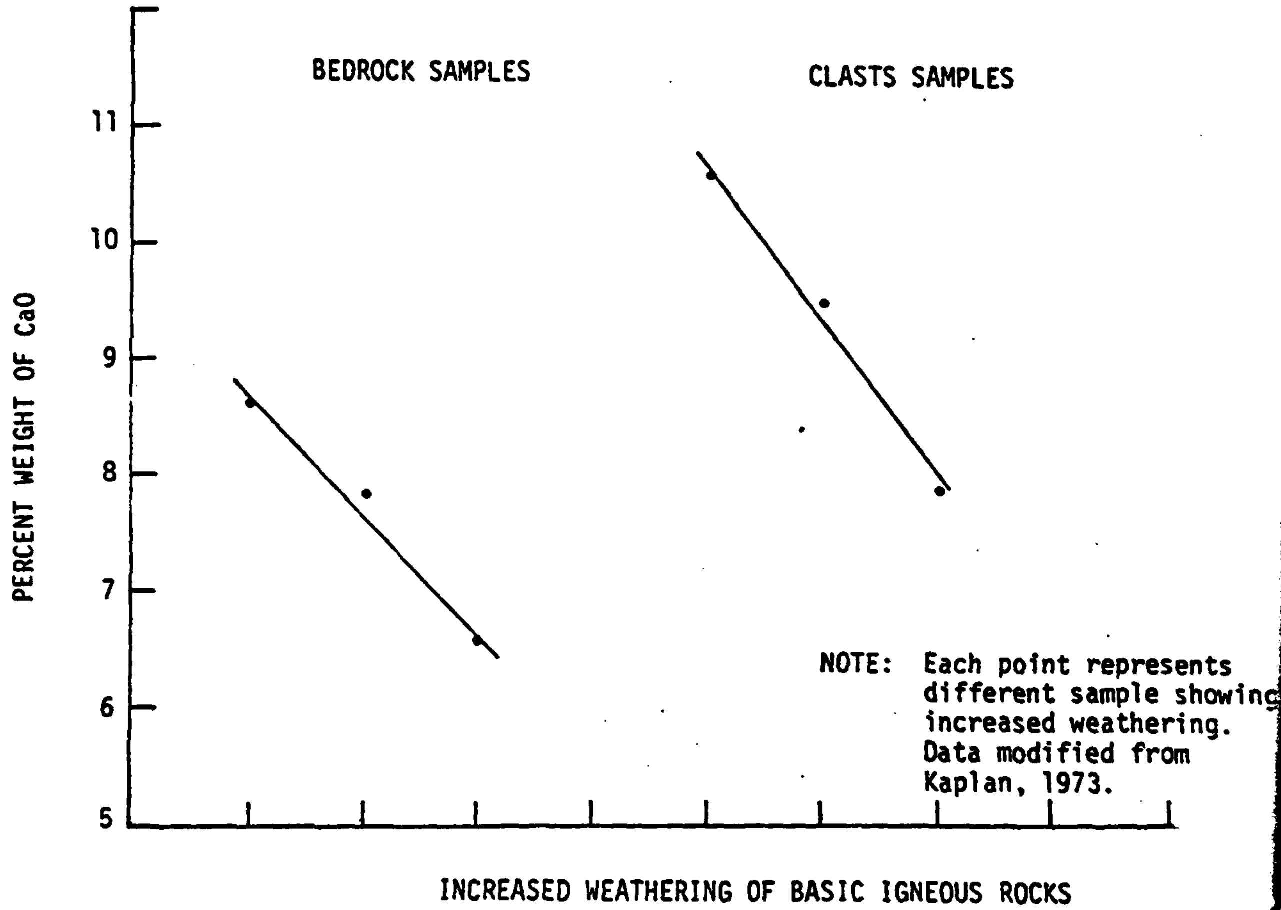



Figure 8. Relationship between percent weight of CaO and stages of weathering on basic igneous bedrock and clasts.

## 4. CHEMICAL AND PHYSICAL PROPERTIES OF PEDOGENIC CALICHE

### Composition and Chemistry of Desert Soil Caliche

The chemical constituents of pedogenic caliche at selected sites in the southwestern United States are given in Table 7. The two most common constituents of caliche in southwestern alluvial basins are calcium carbonate ($CaCO_3$) and silica ($SiO_2$). The caliche matrix is composed typically of 70 to 80 percent $CaCO_3$ and 10 to 20 percent $SiO_2$. The remaining major chemical constituents are MgO, $Al_2O_3$ and $Fe_2O_3$. Chemical analyses of samples studied in this project are summarized in Appendix C.

The mean percentages of chemical constituents in pedogenic caliche sampled around the world are given in Table 7 and Figure 9; the values of the southwestern United States caliche are compared to the world-wide mean. Caliches of a similar stage of development are similar in their chemical composition. In a detailed study of the chemical and mineralogical characteristics of caliches sampled throughout the world Goudie (1972) concluded:

1) microcrystalline calcite is the major mineralogical form of the $CaCO_3$;
2) silica content is usually greater than 10 percent;
3) dolomite (magnesium carbonate) is not common to caliche;
4) gypsum may be concentrated in high percentages locally, but is not regionally significant;
5) clay minerals occur in small fractions as sepiolite and palygorskite.

Table 7. Chemical analyses of caliche at selected sites in the southwestern U. S. as compared to the world mean.

| Location | Chemical Constituent in Percentage | | | | | | |
|---|---|---|---|---|---|---|---|
| | $CaCO_3$ | $CaO$ | $SiO_2$ | $MgO$ | $Al_2O_3$ | $Fe_2O_3$ | $CO_2$ |
| *World Mean Comparison | 79.3 | 42.6 | 12.3 | 3.1 | 2.1 | 2.0 | --- |
| *High Plains New Mexico | 81.3 | 45.6 | 14.3 | 0.3 | 1.0 | 0.7 | 35.7 |
| *High Plains Texas | 71.8 | 40.2 | 22.3 | 0.1 | 0.4 | 0.4 | 31.6 |
| +Sonoran Desert Southern Arizona | 82.4 | 47.0 | 8.9 | 1.0 | 1.2 | 0.3 | 35.4 |
| +Mojave Desert Eastern California & Southern Nevada | 80.7 | 45.1 | 13.1 | 1.4 | 1.1 | 0.1 | 35.6 |

*Data taken from Aristarian (1969) and Goudie (1972),

+Data obtained during this study.

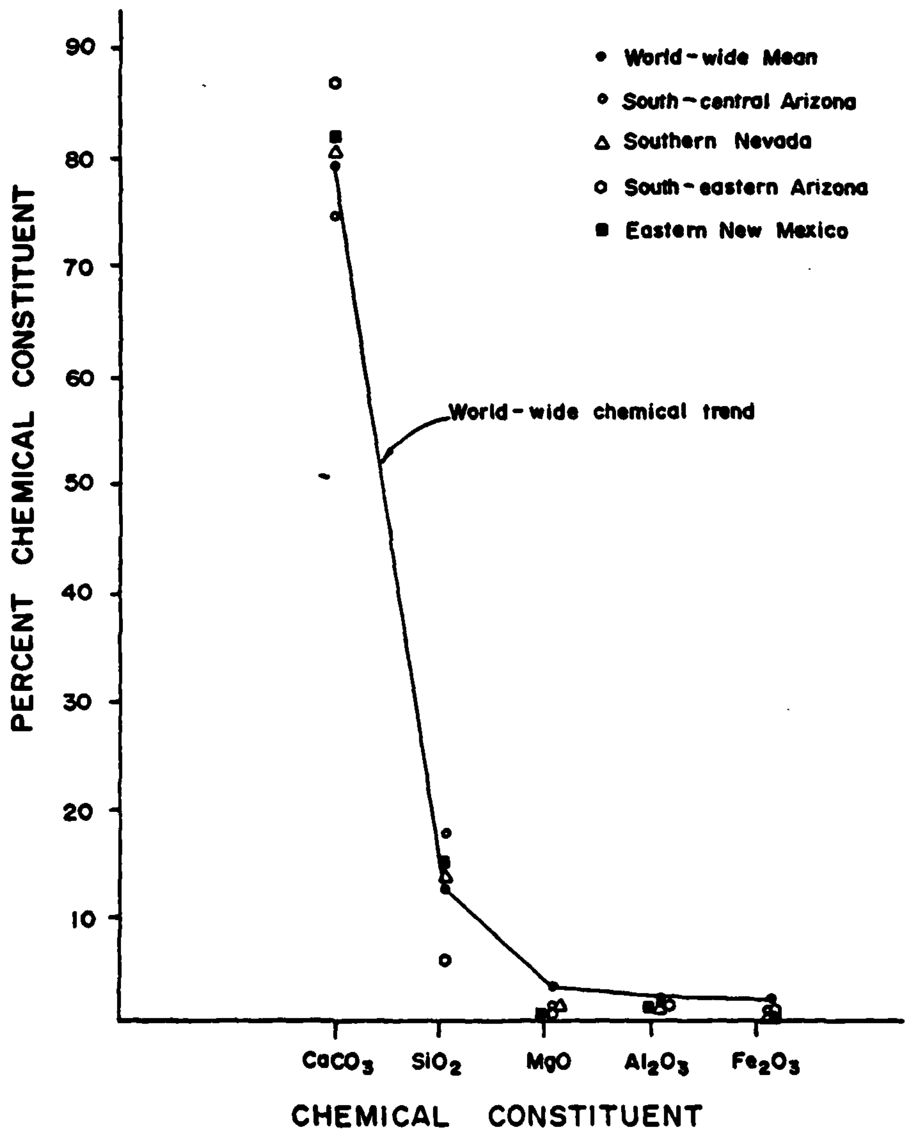



Figure 9. Percent chemical constituents in pedogenic caliche from the alluvial valleys of the Basin and Range compared to world-wide mean of caliche composition.

The addition of calcium carbonate to desert soils is influenced by the solubility of $CaCO_3$ and factors which affect the solubility. Those variables which increase or decrease the solubility of $CaCO_3$ are listed in Table 8. The influence of temperature and $CO_2$ partial pressure on calcium carbonate solubility is illustrated by the work of Miller (1952). Olsen and Watanabe (1959) cautioned that the relationship of $CO_2$ partial pressure to calcite solubility doesn't necessarily apply to calcareous soils. Their research illustrated that calcium carbonate was more soluble in soils than pure calcite under constant $CO_2$ partial pressure. The precipitation of $CaCO_3$ in clay-rich alluvium results in a more soluble form of $CaCO_3$ than calcite. The presence of clay in a medium also resulted in higher concentrations of $Ca^{++}$ and $HCO^3$ and higher values of pH (Olsen and Watanabe, 1959). The exact form of the calcium carbonate in the soil is unknown, but less stable forms of $CaCO_3$ (such as vaterite) are known to occur in the presence of $Mg^{++}$ and organic matter. More soluble phases of calcium carbonate in the presence of clay may explain, in part, the lower $CaCO_3$ accumulations in nongravelly materials as described by Gile et al (1966). More soluble $CaCO_3$ can be carried down further in the soil profile and can be disseminated over a greater vertical distance. Thus, longer time periods are necessary for nongravelly (fine-grained) materials to develop thick carbonate horizons.

Accumulation of Calcium Carbonate Over Time:

Of primary concern to the present study is the origin and accumulation of $CaCO_3$ in desert soils. The amount of calcium

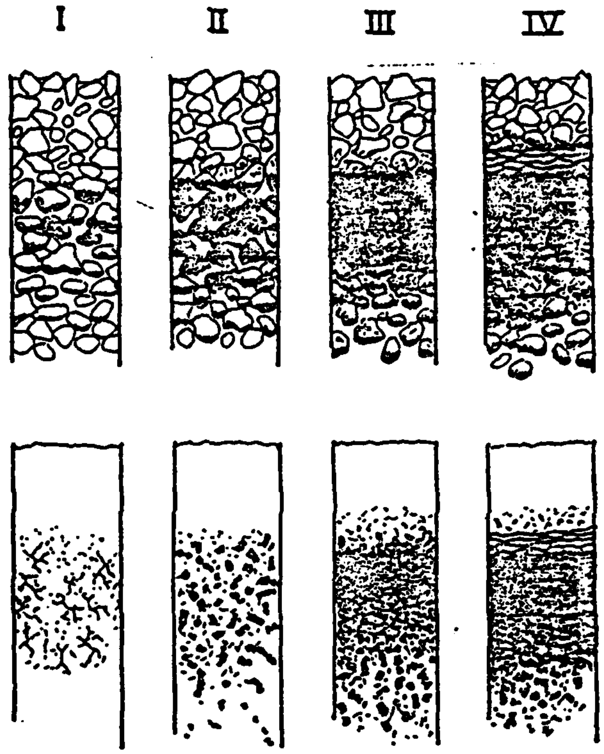
Table 8. Factors influencing $CaCO_3$ solubility in desert soils.

| VARIABLE | INFLUENCE |
|---|---|
| Temperature, T | Decrease solubility with increasing T; $CO_2$ less soluble in solutions with higher T, thus, $CaCO_3$ less soluble. |
| $CO_2$ partial pressure, $pCO_2$ | Decrease solubility with decreasing $pCO_2$. |
| pH | Increase solubility with decreasing pH. |
| Percent clay material | Increase soluble form of $CaCO_3$ in presence of clay. |

carbonate in desert soils change with time. Thus, the similarities of calcium carbonate percentages in Table 7 result from a comparison of similar age or stage of development of the caliche. Those profiles analyzed in Table 7 all contain petrocalcic horizons commonly referred to as calcretes.

The morphology and content of calcium carbonate in soil horizons evolve over time, and this evolution has been divided into four major stages (Gile *et al*, 1966; Gile and Grossman, 1979). Two morphogenetic sequences have been developed for parent material of high- and low-gravel content. These sequences are summarized in Figure 10. Each stage (I through IV) represents increasing calcium carbonate in the horizon of accumulation (Fig. 11). As calcium carbonate is added the morphology of the soil horizon changes becoming more indurated and less permeable. Changes in the percent content of $CaCO_3$ with depth is given for each stage in Figure 12. Calcium carbonate increases in content with depth until stage III. At this time calcium carbonate is not carried deeper into the soil profile; rather, it builds from the plugged horizon upward.

Figure 13 illustrates the amount of time needed to reach the various stages of caliche development. Note that the rate of accumulations changes with mean annual precipitation. Areas of lower mean annual rainfall require longer time periods to reach a stage than areas of higher rainfall. Less atmospheric contribution of calcium and less frequent wetting of the soil horizon causes accumulation rate variation with climate. Well-developed caliches, or Stage IV calcretes, require several hundred thousand years to develop, and




| Stage and general character | Diagnostic carbonate morphology | |
|---|---|---|
| | Gravelly Soils | Nongravelly Soils |
| I<br>Weakest expression of macroscopic carbonate | Thin, discontinuous pebble coatings | Few filaments or faint coatings |
| II<br>Carbonate segregations separated by low-carbonate material | Continuous pebble coatings, some interpebble fillings | Few to common nodules |
| III<br>Carbonate essentially continous; plugged horizon forms in last part | Many interpebble fillings | Many nodules and internodular fillings |
| IV<br>Laminar horizon develops | Laminar horizon overlying plugged horizon | Laminar horizon overlying plugged horizon |

Figure 10. Sketch illustrating stages of pedogenic caliche development over time (after Gile and Grossman, 1979).

Figure 11a. Stage II accumulation in low-gravel parent material.

Figure 11b. Stage IV accumulation in high-gravel parent material.

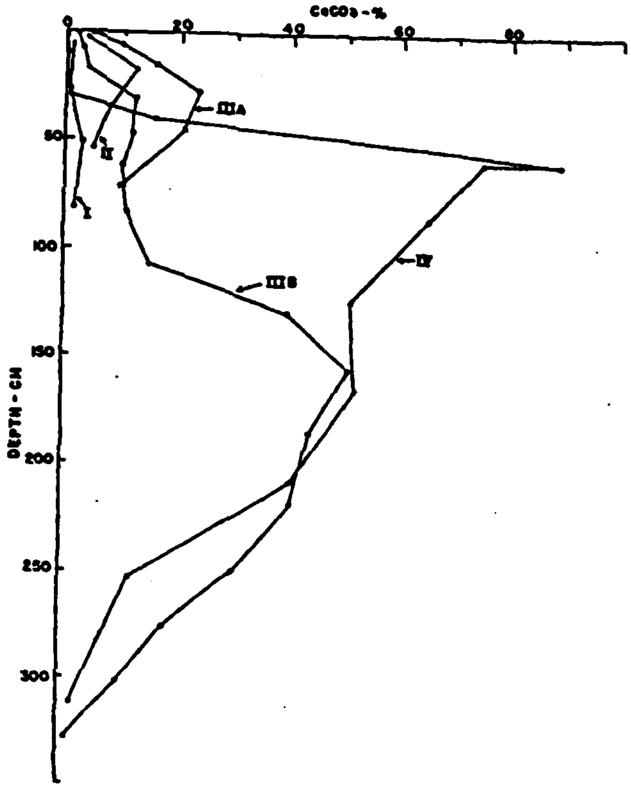



Figure 12. Changes in $CaCo_3$ content with depth in soil profile and with soil stage, or age (after Gile and Grossman, 1979).

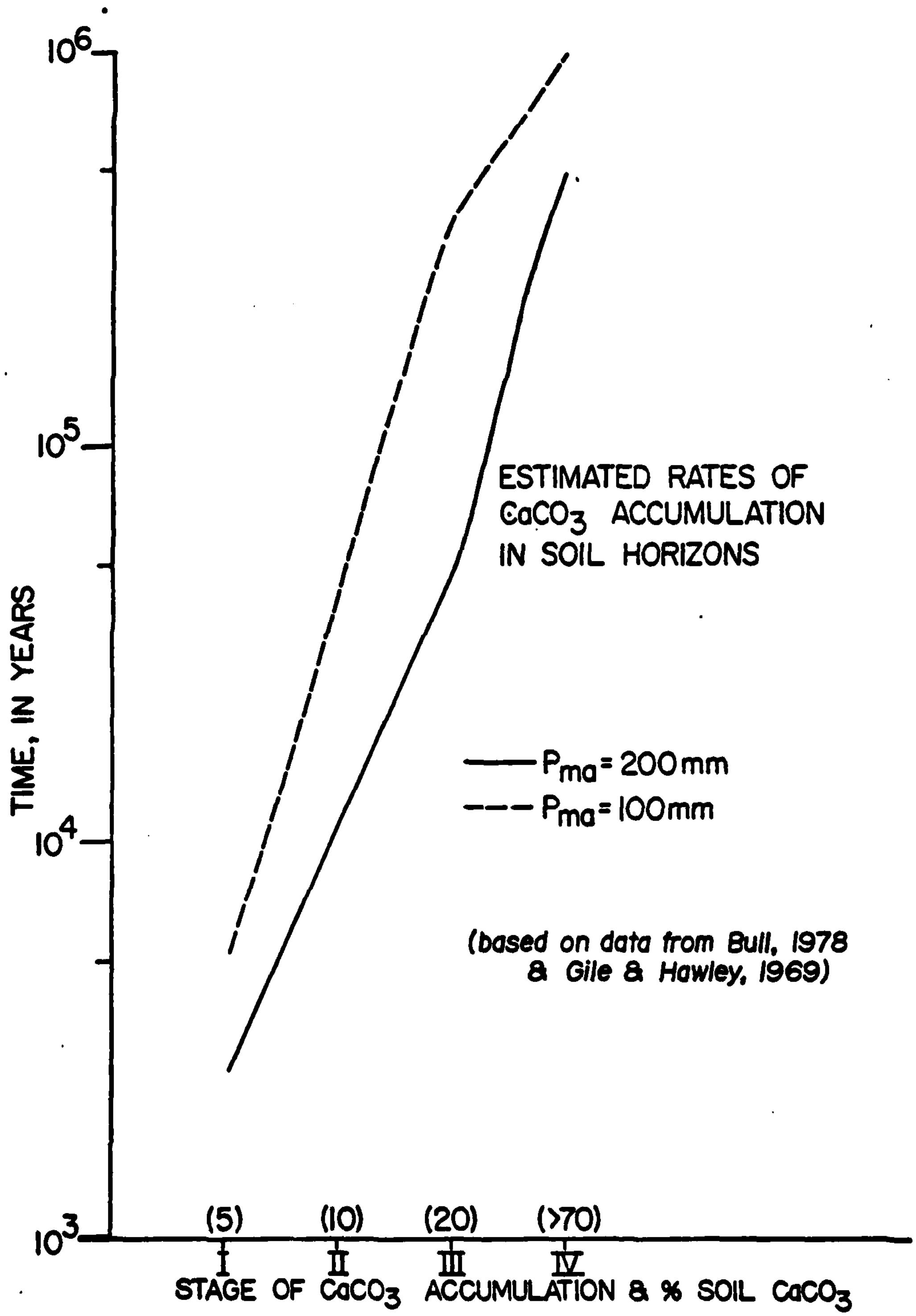



**Figure 13.** Relationship between stage of $CaCO_3$ accumulation and time for two different climatic regimes. Pma = mean annual precipitation.

thus have been forming over the Pleistocene. Stage I and II caliches are more common of Holocene age soils.

Morphologic Properties of Caliche

Numerous studies have been conducted on the macroscopic and microscopic morphology of caliche (Strakov, 1970; Wieder and Yaalon, 1974; James, 1972). The morphology of caliche is time dependent and changes with calcium carbonate content over time. Thus, caliche may range from soft, punky deposits to extremely well-indurated horizons.

Strakov (1970) found that most macroscopic forms of calcium carbonate in pedogenic soils occurred as pellets and crusts. Other macroscopic forms of secondary calcium carbonate include breccias, concretions, honeycomb textures, laminae, nodules and plates. Dissolution features such as pipes and vugs are common, as well as cracks, microspeleothems and slickensides. Reeves (1976) gives a comprehensive summary of macroscopic features found in caliche.

Features similar to those on macrocscopic scales occur in a diminutive scale. These include pelletoids, breccias, and laminations. James (1972) described five major types of caliche textures associated with three types of calcium carbonate crystal morphologies (Fig. 14). The most common type of crystal morphology in pedogenic caliches is micrite. Textures such as coatings, crusts (laminae) and pelletoids are common in pedogenic caliche of the southwestern United States (see Appendix D). Adams (1974) analyzed caliche profiles in southern Nevada and found several microscopic

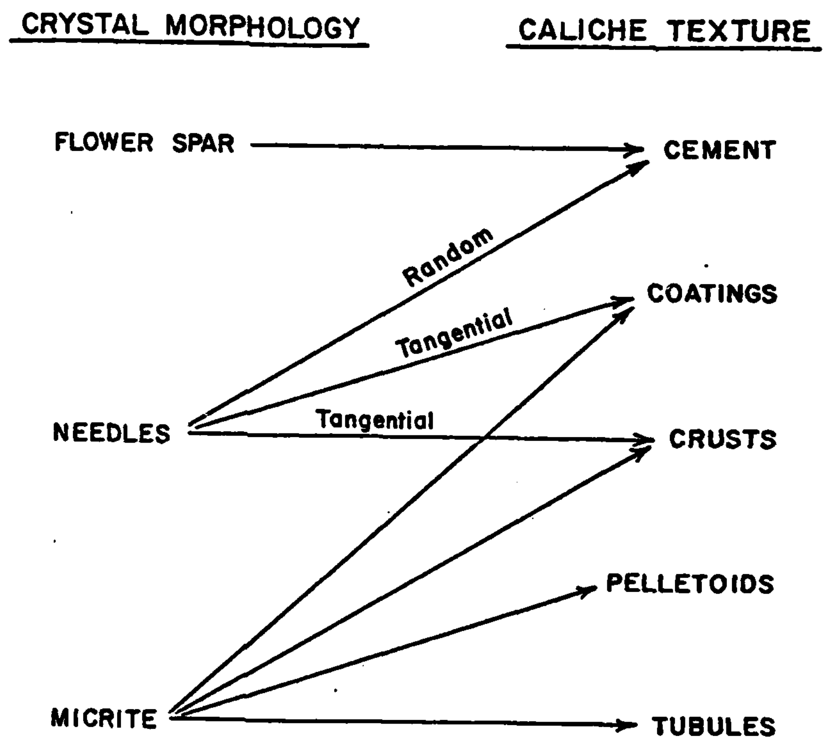



Figure 14. Relationship between crystal morphology and caliche texture (after James, 1972).

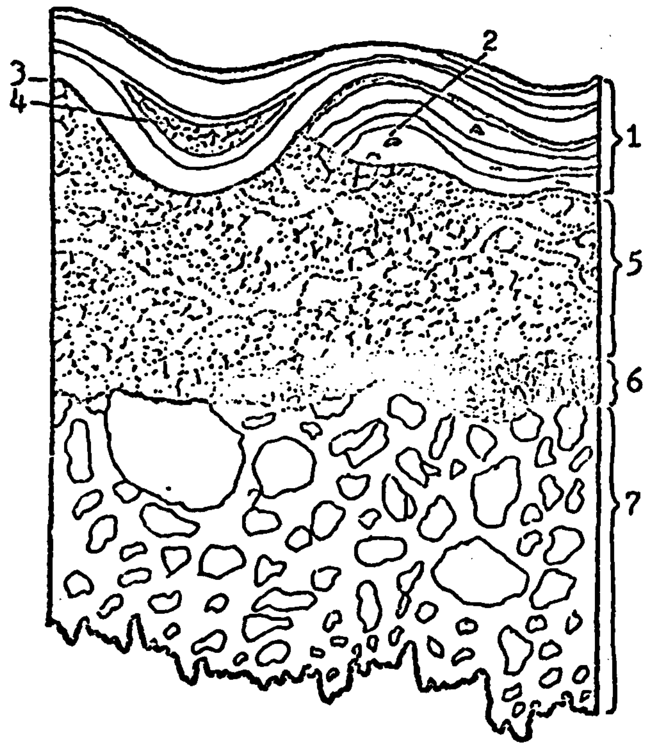
properties that are similar to secondary calcium carbonate deposits in the Caribennean and Middle East (Table 9). Adams also found that the bulk of caliche consits of micrite. One common feature in pedogenic and nonpedogenic caliche deposits is that of laminar layers. A typical, composite stratigraphic section of a laminar layer is given in Figure 15. Two dominant forms of layering occurs: (1) dense, well-laminated layers and (2) mottled, porous layers. Mottled porous layers develop by replacement and cementation of clastic detritus by microcrystalline calcite. Dense, well-laminated layers form by periodic wetting and drying on relatively impervious surfaces. In most cases the porous layers are overlain by the dense layers implying a genetic relationship (Adams, 1974).

In the present study, several caliche profiles were sampled in the four study areas of Arizona and Nevada. Most sites sampled included Stage IV (petrocalcic) caliche. At each sample site, the grain size distribution for clasts over 2 mm were measured in the field and the lithologic composition of these clasts were determined. In the lab petrographic analyses provided data on mineral constituents and microscopic properties. Field and laboratory data are summarized in Appendix D and E. Results of this study are summarized below:

1) The majority of pedogenic caliche is composed of micrite occurring as grain coatings or as small aggregates;
2) The majority of minerals fragments in the $CaCO_3$ matrix is quartz and the quartz shows some degree of weathering;
3) pelletoidal structures are common and may occur in laminae or in random orientations;
4) Mineral composition and fragment rounding indicate a low

Table 9. Microscopic textures in pedogenic caliche horizons.

| Alteration | Barbados | Israel | Florida | Nevada |
|---|---|---|---|---|
| Solution | X | X | X | X |
| Brecciation | X | X | X | X |
| Recrystallization (to microspar) | X | X | X | X |
| Micritization | X | | X | X |
| Boring | X | | X | |
| **Precipitation** | | | | |
| Micrite-clotted | X | X | X | X |
| Micrite-pelletoids | X | | X | X |
| Needle fibers-random | X | X | X | X |
| Needle fibers-tangential | X | X | X | X |
| Flower calcite spar | X | | X | X |
| Clear calcite spar | X | X | X | |
| Coated pelletoids | X | | X | X |
| Coated allochems | X | | X | |
| Coated breccia fragments | X | | | |
| Coated fractures | X | X | X | X |
| Laminated crusts-micrite and needle fibers | X | X | X | X |
| Laminated crusts-merged pelletoids | X | X | X | |
| Laminated crusts-calcite spar | X | X | X | X |
| Fine tubules | X | | X | |




LEGEND

1=Dense, well-laminated layer

2=Organic fragments

3=Truncation of lower laminar layers by the uppermost dense, well-laminated layer.

4=Detrital lens

5=Mottled, porous laminar layer

6=Microcrystalline rind

7=Carbonate alluvium (may be cemented)

Figure 15. Composite stratigraphy of a laminar layer in a Stage IV pedogenic caliche (after Adams, 1974).

textural maturity which suggests that $CaCO_3$ deposits result from weathering processes and very little transportation of fragments occur before cementation;

## Effect of Calcium Carbonate Cementation on Alluvium and Soil Properties

Caliche is a natural cementing agent in desert soils and alluvium. The major effect of caliche development is the induration of previously unconsolidated alluvium and binding clasts into particle sized larger than the in-situ grain size. The amount of calcium carbonate accumulation and induration increases with time. Thus, older desert soils, given the proper conditions, will be better cemented by calcium carbonate than younger desert soils. This relationship is shown in Figure 10. The physical porperties of soils and unconsolidated alluvium change with increasing amounts of calcium carbonate; therefore, the physical properties of the soils will vary with their age.

Compressive Strength of Calcium Carbonate Cemented Materials:

Gile (1961) determined that the compressive strength of soils (both air dry and moist) increases logarithmically with increasing calcium carbonate content according to the equation: $\text{Log } Y = 2.10 + 0.18X$ where $r = 0.78$ at the 1 percent level, $Y$ = compressive strength, $X$ = percent carbonate. Compressive strength measurements by Gile ranged from 85 to 7880 psi on air dried samples and from 3 to 5430 psi on moist samples. The mean values of the compressive strength for non-indurated, air dried samples is 21 times the mean of indurated caliche. Additionally, moist-compressive strength of petrocalcic horizons average approximately 8 times higher than air-dried calcic, or poorly indurated, horizons. Laminar layers, which have the highest relative percent of calcium carbonate compared to other caliche types, have compressive strengths similar to concrete (Gile, 1961).

Bulk Densities of Caliche:

Measurements of bulk densities, of caliches are sparse. Gile (1961) and Netterbert (1971) have made measurements for caliches in New Mexico and South Africa, respectively. Their results are discussed below.

The range in values of bulk densities for caliche in southeastern New Mexico is 1.3 to 2.2 $g/cm^3$. The bulk density of soils increases linearly with inncreasing calcium carbonate content according to the equation: $Y = 1.57 + 0.0037 X$, where $r = 0.58$ at the 1 percent level, $Y$ = bulk density, $X$ = carbonate content. Highest bulk densities are associated with petrocalcic horizons and laminar layers.

Infiltration Rates of Caliche:

Detailed studies of water infiltration on caliche horizons have been conducted by Gile (1961) and Colley <u>et al</u> (1973). Their data and results are discussed below.

The infiltration rate of desert soils decreases with increasing calcium carbonate content and induration. Older soils with well developed caliche have the lowest infiltration rates. Non-pedogenic caliches, such as gully-bed cementation, will have very low infiltrations, too. Laminar layers are essentially impervious zones as their hydraulic conductivities average 3.12 x 105 cm/min. Fractured caliche horizons would increase the permeability. However, field observatons indicate that fracturing of caliche is limited to banks near incised gullies and washes, and that fractures are commonly re-cemented with laminar layer deposits. The permeability of the desert soil is also related to the depth of burial of the caliche horizon as well as the degree of **induration**. Infiltration rates are slightly higher for caliches in moister climates as the caliche occurs at greater depths. Additionally, infiltration rates on desert surfaces covered with caliche rubble may be slightly higher in that the upper few centimeters are composed of fragmented caliche and silt. Caliche will serve as a barrier to downward percolating water, and such barriers result in increased runoff.

The relationship between infiltration rates and the amount of calcium carbonate content has been evaluated quantitatively by Gile (1961). He found the following relation: Log Y = 0.78 0.02X, where r = 0.08 at the 1 percent level, 0 Y = infiltration rate, X = percent carbonate.

In summary, the two major variables influencing infiltration rates are calcium carbonate content and depth of caliche in the soil profile. The lower the content and deeper the horizon, the higher the infiltration rate.

Engineering properties of soils are reviewed by Reeves (1976). Reeves concluded that older soils have lower value of linear shrinkage, plasticity index and water absorption due to the $CaCO_3$ increase. Gile and Grossman (1979) provide measurements of Atterbury Limits for desert soils in New Mexico. Values for liquid limit and plastic index in calcium carbonate horizons are summarized in Table 10. The range in the liquid limit for caliche horizons with high calcium carbonate content ranges from 24 to 36; plastic index values range from 2 to 18. These samples include carbonate and noncarbonate clay.

Property Variations in a Desert Soil Profile

Physical and engineering properties vary within a single soil protile as well as varying across the desert landscape. Variations of physical properties within a soil profile result from differences in calcium carbonate content and depth. In addition, physical properties will vary with soils of different ages due to changes in calcium carbonate content over time. These variations in a soil profile are illustrated in Figure 16. For a soil of given age in Figure 16, variations in physical properties with depth can be seen in each associated row, and for soils of differing ages, changes in a single property through time can be seen in each column. Older soils with greater calcium carbonate contents have the greatest variation in properties within a single profile. Variations in soil properties over the landscape of an alluvial valley will be discussed in later sections. However, older soils tend to be best

Table 10. Liquid limit (LL) and plastic index (PI) for caliche horizons.

| Depth (cm) | Liquid Limit | Plastic Index |
|---|---|---|
| 201-231 | 25 | 10 |
| 71-112 | 28 | 11 |
| 23-36 | 29 | 2 |
| 51-64 | 33 | 13 |
| 64-86 | 27 | 11 |
| 112-142 | 32 | 10 |
| 56-71 | 28 | 10 |
| 71-86 | 23 | 7 |
| 76-112 | 33 | 12 |
| 79-99 | 36 | 18 |
| 173-190 | 24 | 8 |
| 33-58 | 24 | 6 |
| 58-86 | 28 | 11 |

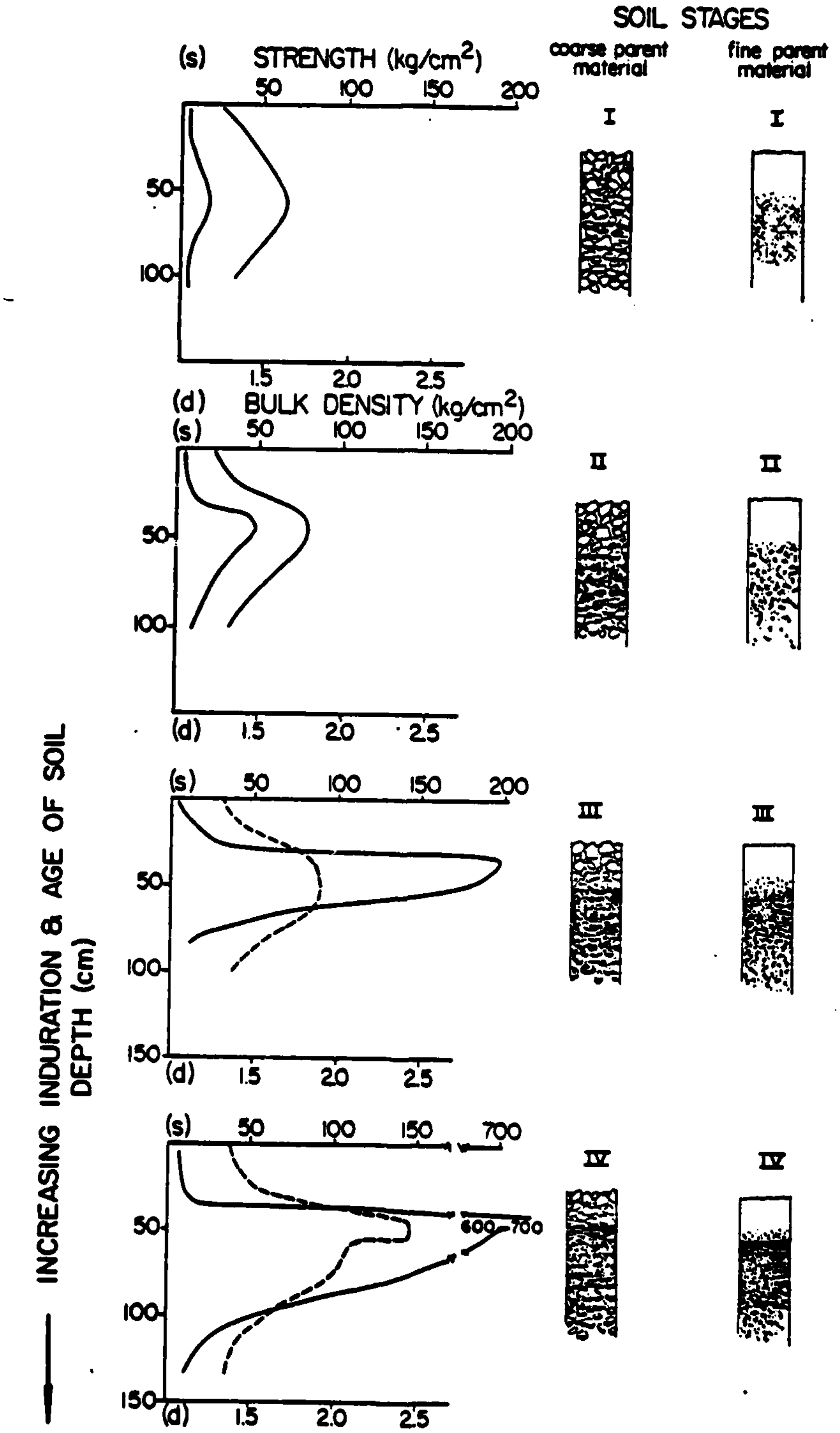



Figure 16. Variations in physical properties of pedogenic caliche with depth in soil profile and with soil age.

preserved in alluvial valleys of the Basin and Range Province along the mountain fronts. Younger soils are found commonly with in the basin center. Details on soil-landscape associations will be discussed in later sections.

## 5. TERRAIN ASSOCIATIONS AND EFFECTS OF CALICHE ON ALLUVIAL BASIN LANDSCAPES

Different types of caliche occur on different landforms and slope conditions (Table 11). Calcic and petrocalcic horizons as well as laminar layers have the most diverse landform associations and, therefore, have regional significance (compare Tables 2 and 11). These caliche types are common to slopes less than $10^{\circ}$, which are typical in desert basins (Wells, 1976; Cooke and Warren, 1973); therefore, these soil-landform associations will be of significant concern to the MX System which are designed for low-valley slope angles. Induration of the alluvium and soil results in horizons that are less erodable than uncemented materials. Changes in the erodibility of alluvial landforms with $CaCO_3$ accumulation results in feedback between caliche development and landscape development. The and stability of the terrain is necessary for woil development and calcium carbonate accumulation. Thick $CaCO_3$ accumulations influences terrain development by making it less erodable; thus, the development of secondary calcium carbonate horizons in alluvial materials will affect the morphology of the landscape. The geomorphic significance of caliche on desert, alluvial landscapes in

Table 11. Summary of terrain characteristics and types of $CaCO_3$ cementation.

| TYPE | LANDFORM ASSOCIATION | SLOPE ASSOCIATION* | RANKING IMPACT ON LANDSCAPE+ |
|---|---|---|---|
| Calcic Horizon | Alluvial fan, terrace floodplans, playas, piedmont, pediment | Low to Moderate | 5 |
| Petrocalcic Horizon | Alluvial fan, terrace, piedmont, pediment | Low | 1 |
| Gully-Bed Cementation | Ephemeral washes (beds and lower banks), gullies or rills | Low to Moderate | 3 |
| Case-Hardening | Any surface exposure of unconsolidated alluvium or colluvium | Low to Extreme | 2 |
| Laminar Layer | Alluvial fan, terrace piedmont, pediment, hillslopes (colluvial or bedrock) | Low to Extreme | 4 |
| Caliche Rubble | Abandon alluvial fan surfaces, terraces | Low | 6 |

*Low: less than $10^{o}$

Moderate: greater than $10^{o}$, less than $30^{o}$

Extreme: greater than $30^{o}$

+Influence or feedback of caliche on landscape development in desert basins

Nevada and Arizona have been discussed by Lattman (1973), VanArsdale (1974), and Wells (1976). Caliche cementation can influence the desert terrain in the following ways:

(1) preservation alluvial fan and terrace surfaces and increase their frequency per basin.

(2) preservation of the original slope and morpholgoy of the fan or terrace surface.

(3) Maintenance of steep slopes (up to vertical) and high banks along drainage ways.

(4) alteration of the morphologic development of washes and arroyos in cross and long profile.

(5) decrease in the frequency of drainage lines developed on alluvial materials.

## Influence of Caliche on Desert Fluvial Systems

The geomorphic effects of caliche on alluvial fan morphology is described in detail by Lattman (1973). The influence of calcium carbonate sementation on washes and gullies is described by VanArsdale (1974) and Wells (1976).

The hydraulic geometry and channel patterns of washes are controlled by caliche horizons that are exposed at the surface. Channels flowing on caliche horizons (i.e. banks are composed of uncemented alluvium) will have high width-depth ratios. Additionally, these channels may be braided and/or highly sinuous. Washes incised in to caliche (i.e. banks are cemented) will have lower width-depth ratios. In these reaches channel infiltration is minimal. Consequently, the discharge of streams which drain areas of caliche should be higher. To test this hypothesis, computed discharge (based on flood marks rather actual flow) is plotted against the drainage area above a given cross-section where discharge measurements were obtained (Fig. 17). Computed discharge and drainage area are related to each other by a power function, and equations describing this relationship are:

Equation 1: $Q_c = 10.4\ A_d^{0.72}$ for watersheds without caliche

Equation 2: $Q_c = 25\ A_d^{0.36}$ for watersheds with caliche

where,

$Q_c$ computed discharge

$A_d$ = drainage area

$r = 0.990$ at 5 percent level for Equation 1

$r = 0.983$ at 5 percent level for Equation 2

The logarithmic plots of these variables and the regression equations indicate that drainage basins with caliche have higher computed discharges at selected cross-sections than those basins

without caliche. In the reaches confined by the caliche horizons channel sinuosity decreases and straight channel segments occur. After the wash or gully has incised through the cemented horizon, infiltration increases, the width depth ratio increases, and channel sinuosity increases.

Alluvial fan surfaces, which are heavily cemented and display calcic and petrocalcic horizons as well as laminar layers, promote excessive surface runoff as overland flow (Cooley et al, 1973). In such regions, the drainage texture, or the drainage density and

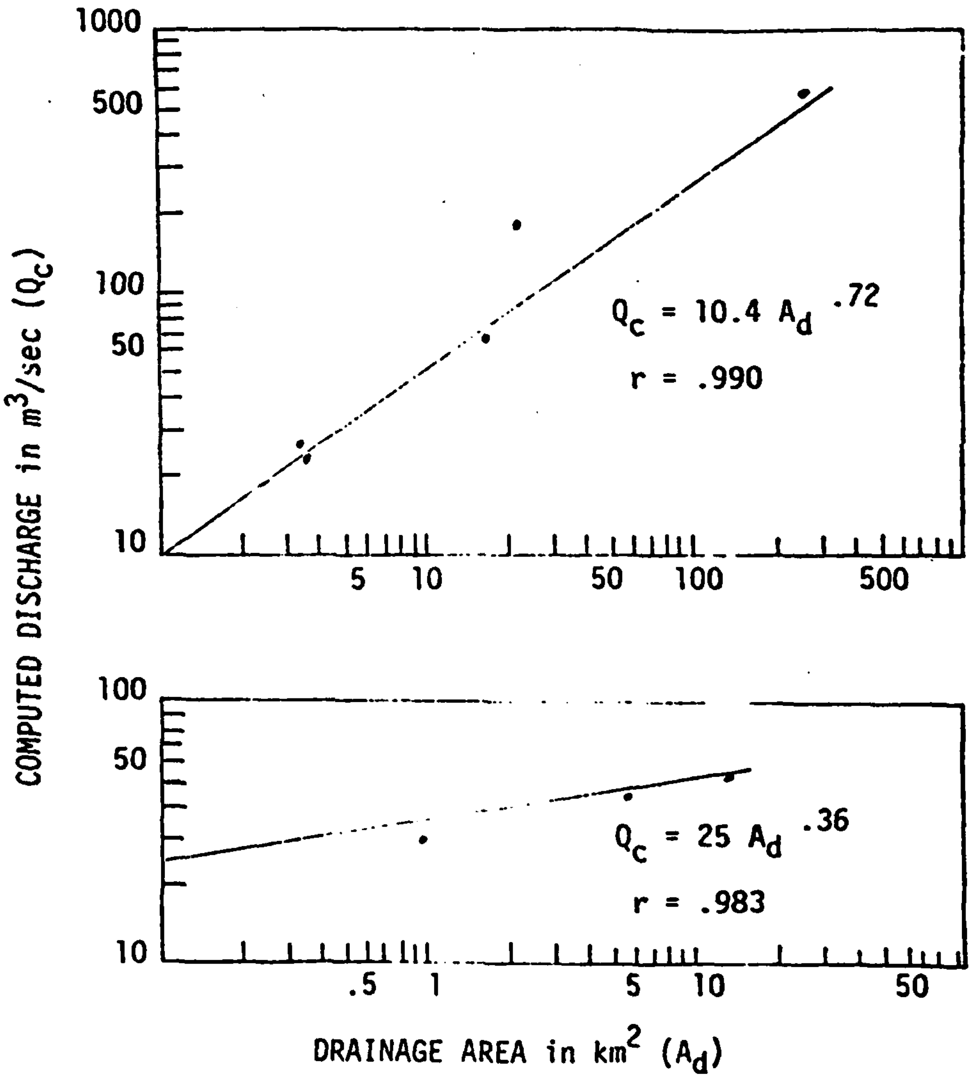



**Figure 17. Computed discharges of desert streams at selected cross-sections in areas without (upper) and with (lower) pedogenic caliche.**

drainage frequency, should be affected by this increase in overland flow. Specifically, fluvial systems developed on caliche should have a coarser texture (fewer surface streams). The Mann-Whitney U is used to test the relationship between drainage density and drainage frequency of watersheds with and without caliche. Results of this statistical test are given in Table 12. It can be seen that drainage density is not statistically different at the 5 percent level in basins with and without caliche. However, drainage frequency is statistically different for these two basin types. Drainage basins with caliche have low values of drainage frequency, and are usually less than 16 (Table 12).

## 6. FACTORS INFLUENCING THE DISTRIBUTION AND FORMATION OF PEDOGENIC CALICHE IN ALLUVIAL BASINS

Pedogenic caliche (calcic and petrocalcic) is the most regionally extensive secondary calcium carbonate deposit in the near-surface alluvium of desert basins (see section 3). During the present study, those major variables which influence the formation and distribution of pedogenic caliche were evaluated. Those major factors influencing soil development include time, climate, parent material, topography and biota. These basic soil-forming variables have been modified to include variables directly related to the accumulation of calcium carbonate in the soil profile. These variables are listed in Table 13, and include time, climate parent material, stability of land surface, hydrology, topography, and

Table 12. Mann-Whitney U Test for relationship of drainage density and drainage frequency of desert drainage basins with and without indurated caliche.

| Drainage Basin | Drainage Density | Drainage Frequency |
|---|---|---|
| IMQ-C | 5.35 | 16.14 |
| IMQ-D | 8.01 | 23.34 |
| CPQ-A | 4.57 | 11.11 |
| CPQ-B | 3.40 | 4.16 |
| CPQ-C | 9.00 | 23.30 |
| CPQ-D | 6.25 | 11.54 |
| BHMQ-A | 6.27 | 16.72 |
| BHMQ-B | 3.17 | 16.10 |
| EMQ-A | 11.57 | 50.23 |
| EMQ-B | 19.33 | 69.57 |

basin with indurated caliche deposits = C

basin without indurated caliche deposits = N

---

Drainage Density Test

| 3.17 | 3.40 | 4.57 | 5.35 | 6.25 | 6.27 | 8.01 | 9.00 | 11.57 | 19.33 |
|---|---|---|---|---|---|---|---|---|---|
| N | C | C | N | C | N | N | C | N | N |

$n_2 = C = 4$ $U = 8$

$n_1 = N = 6$ $\alpha = 0.05$ table value - 3, therefore accept $H_o$ .

U value indicated drainage densities same in basins of different surficial deposits.

---

Drainage Frequency Test

| 4.16 | 11.11 | 11.54 | 16.10 | 16.14 | 16.72 | 23.30 | 23.35 | 50.23 | 69.57 |
|---|---|---|---|---|---|---|---|---|---|
| C | C | C | N | N | N | C | N | N | N |

$n_2 = C = 4$ $U = 3$

$n_1 = N = 6$ $\alpha = 0.05$ table value - 3, therefore reject $H_0$ .

U value indicates drainage frequency different in basins of different surficial deposits.

Table 13. MAJOR VARIABLES INFLUENCING PEDOGENIC CALCRETES FORMATION & DISTRIBUTION IN ARID ALLUVIAL BASINS

1. TIME
2. CLIMATE
   - PRECIPITATION
   - EVAPORATION
   - WIND
   - TEMPERATURE
3. PARENT MATERIAL
   - COMPOSITION
   - THERMAL PROPERTIES
   - WEATHERING STABILITY
   - TEXTURAL PROPERTIES
4. STABILITY OF LAND SURFACE
   - TECTONICS
   - RATES OF SEDIMENTATION & EROSION
   - ERODIBILITY OF SURFACE MATERIALS
5. HYDROLOGY
   - INFILTRATION
   - SHEETFLOW
6. TOPOGRAPHY
   - SLOPE
   - ROUGHNESS
   - DISSECTION
7. VEGETATION

vegetation.

A hierarchy of the relative importance among these variables is only practical at site-specific locations. That is, at one location in an alluvial valley, parent material may be the most important variable influencing the occurrence of caliche; whereas, in another location within the same basin, stability of the land surface may be of greater importance in the formation and preservation of caliche. Perhaps the four most important variables influencing caliche formation and distribution are time, climate, parent material and landscape stability. In the sections below, the role of each variable is evaluated for its relative influence on caliche occurrence in order to development method(s) of predicting caliche distribution in alluvial valleys of the southwestern United States.

## Time and Topography

In the previous sections of this report, it was demonstrated that calcium carbonate accumulation in soil profiles is influenced by the age of the soil profile. The age of a soil profile is related to the age of the alluvium and land surface upon which it develops. In most alluvial basins of the Basin and Range Province, the spatial arrangement of alluvial deposits and geomorphic surfaces developed upon them reflect their relative ages.

Alluvial basins can be subdivided into two landscape units: valley piedmont and valley axis (Fig. 18). Typical arrangement of alluvial deposits and geomorphic surfaces for these two landscape units are given in Figures 19 and 20. Older deposits and associated

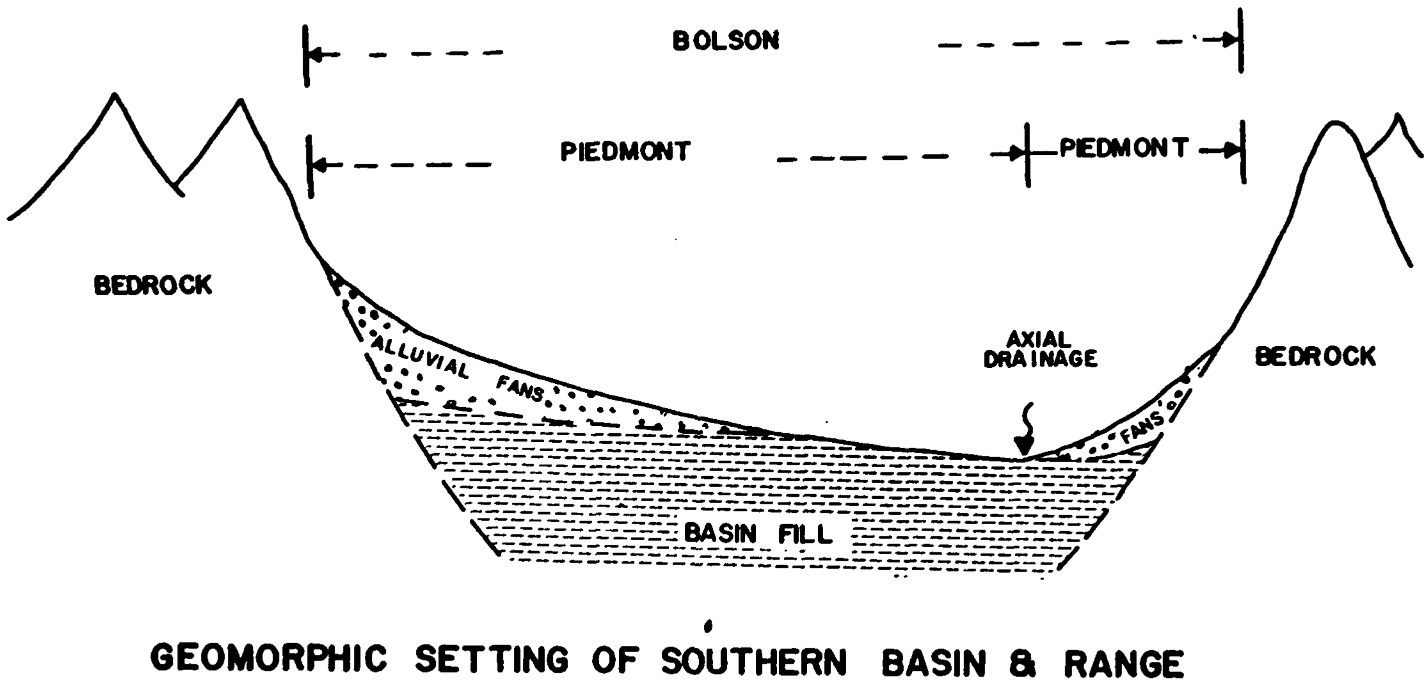
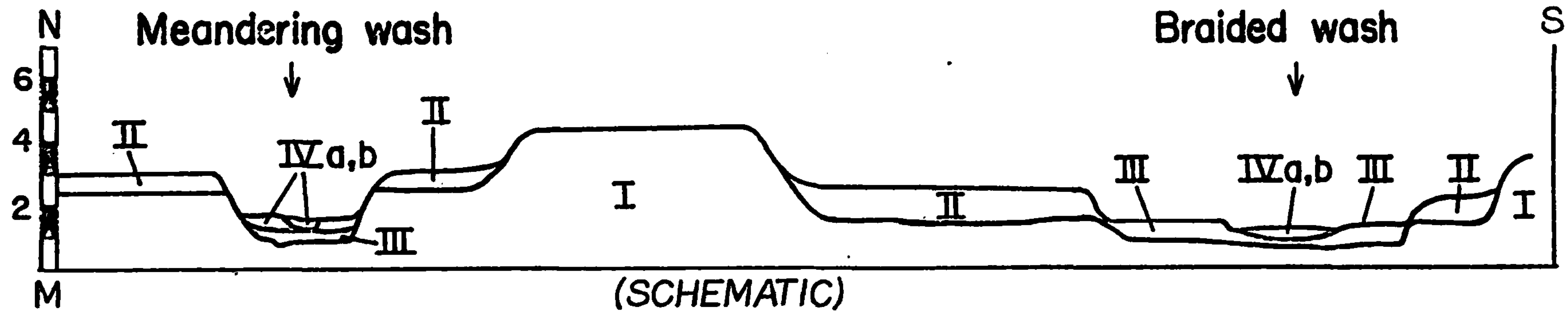
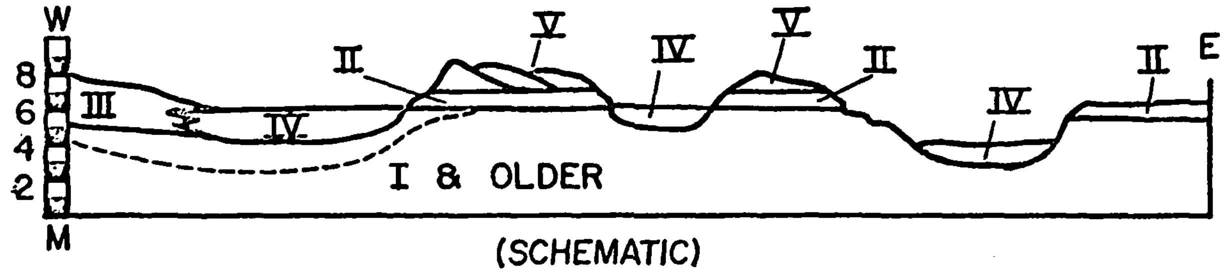



Figure 18. Sketch showing two major landscape units, piedmont and axial drainage, in typical alluvial basin.




| | DEPOSITS | |
|---|---|---|
| HOLOCENE | IVa,b | FAN & INSET FILL |
| HOLOCENE | III | INSET FILL & FAN |
| PLEISTOCENE | II | FAN & TERRACE FILL |
| PLEISTOCENE | I | FANGLOMERATE |

Figure 19. Spatial arrangement of alluvial deposits and geomorphic surface perpendicular to valley piedmont slope.




DEPOSITS

| | | |
|---|---|---|
| HOLOCENE | V | STABILIZED DUNES |
| | IV | ACTIVE AXIAL CHANNELS |
| | III | ACTIVE FANS |
| | II | TERRACE DEPOSITS |
| PLEISTOCENE | I & OLDER | FANGLOMERATE & OLDER BASIN FILL |

Figure 20. Spatial arrangement of alluvial deposits and geomorphic surfaces perpendicular to valley axis slope.

geomorphic surfaces, such as I and II in Figures 19 and 20, commonnly have better developed caliche horizons. Along valley piedmonts the topography is typically stepped with the older surface begin the the highest and younger surfaces being lower and inset into the older. This relationship changes down-piedmont toward the valley axis. Near the valley axis, younger deposits overlap the older surfaces and the soils may be buried, truncated or eroded away (Fig. 20).

Recent dating of pedogenic carbonates on desert piedmonts in southeastern California (Ku et al, 1979) demonstrate the age relationship between geomorphic surface and its topographic level. Figure 21 illustrates the relationship between age of soil horizon and level of geomorphic surface. Older soil horizons may be in excess of 300,000 and should have Stage IV type caliche. Lower surfaces with ages of less than 10,000 yr would have only Stage I type caliche.

In the valley-axis landscape, stepped topography only occurs if the axial drainage has been downcutting through geologic time. Thus, a series of surfaces with the oldest at the highest topographic position and the youngest with the lowest position would be preserved. In closed valley systems, the basin axis has been aggrading through geologic time, and stepped or sequence geomorphic surfaces either are not preserved or do not form (Fig. 20).

## Climate

The role of climatic variables on caliche formation in desert

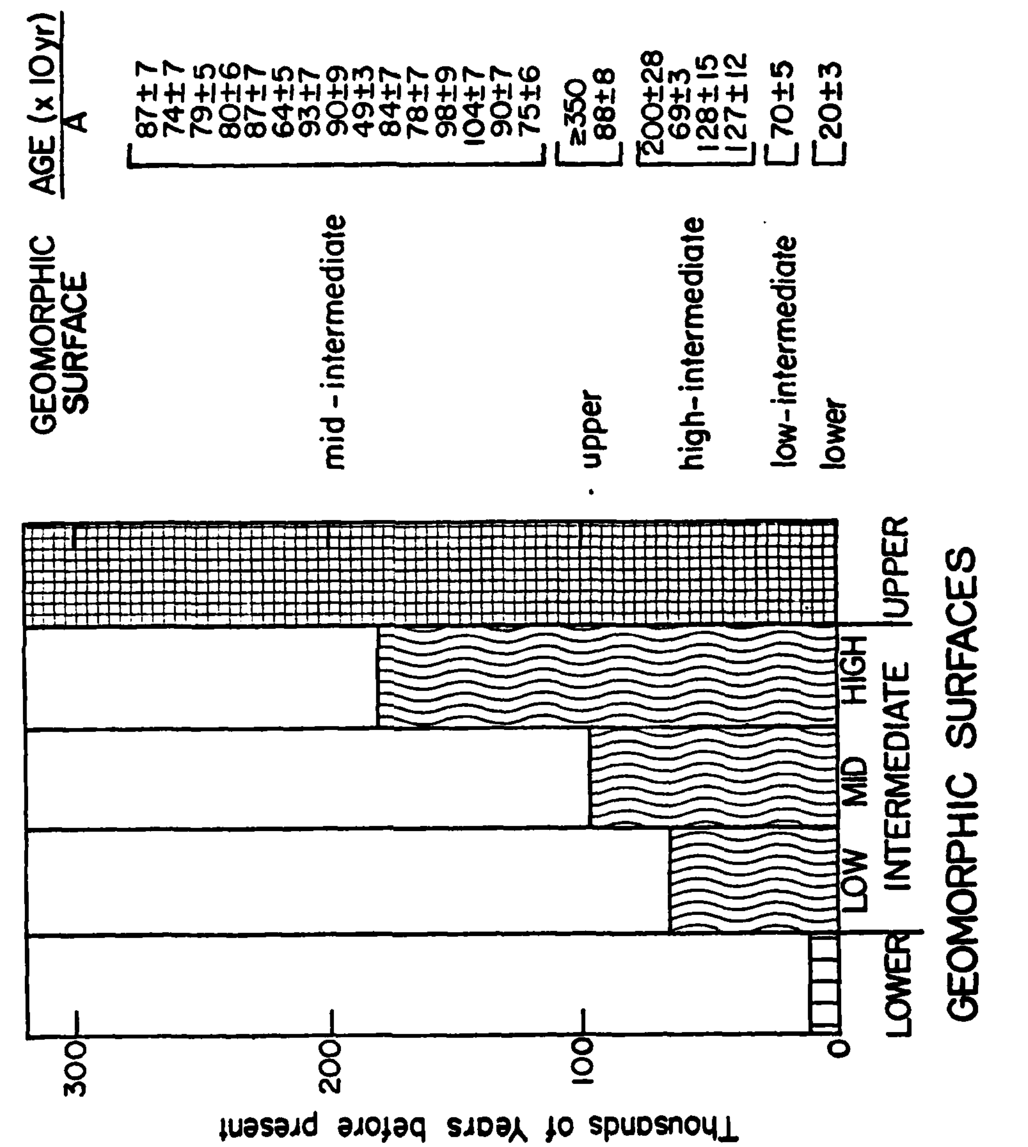



Figure 21. Age relationship of pedogenic carbonate on geomorphic surfaces of a valley piedmont (After Ku et al, 1979).

alluvial valleys is significant. Precipitation, evaporation, wind and temperature are all important parameters affecting the amount, rate and depth of secondary calicum carbonate accumulation. Wind and rainfall supply the calicum ions to the land surface. Rain water infiltrates the ground carrying calcium carbonate to a given depth of wetting. The rainfall amount, duration and intensity as well as the amount of evaporation influence the depth of carbonate accumulation. Climatic conditions have not remained constant over the Quaternary; periods of greater rainfall and lower evaporation coccurred at various intervals in the past 300,000 yrs. These changes would increase the amount of carbonate accumulation creating thicker and better developed caliche horizons.

The depth to caliche horizons below the land surface changes with rainfall amount (approximately mean annual precipitation). Figure 22 illustrates changes in the depth of caliche horizons along desert piedmonts in southern New Mexico. Caliche horizons commonly occur at depths in excess of 1 m where mean annual precipitation is greater than 30 cm. Arkely (1963) determined a quantitative relationship between depth to pedogenic caliche and mean annual precipitation:

Equation 3: $Dca = 1.63\ (Pm\ \ 0.45)\ r = 0.76$

$Dca$ = depth to caliche

$Pm$ = mean annual precipitation

For pedogenic caliches a significant statistical correlation has been found between depth to the cemented horizon and the annual rainfall amount (Table 14). Both linear and statistical

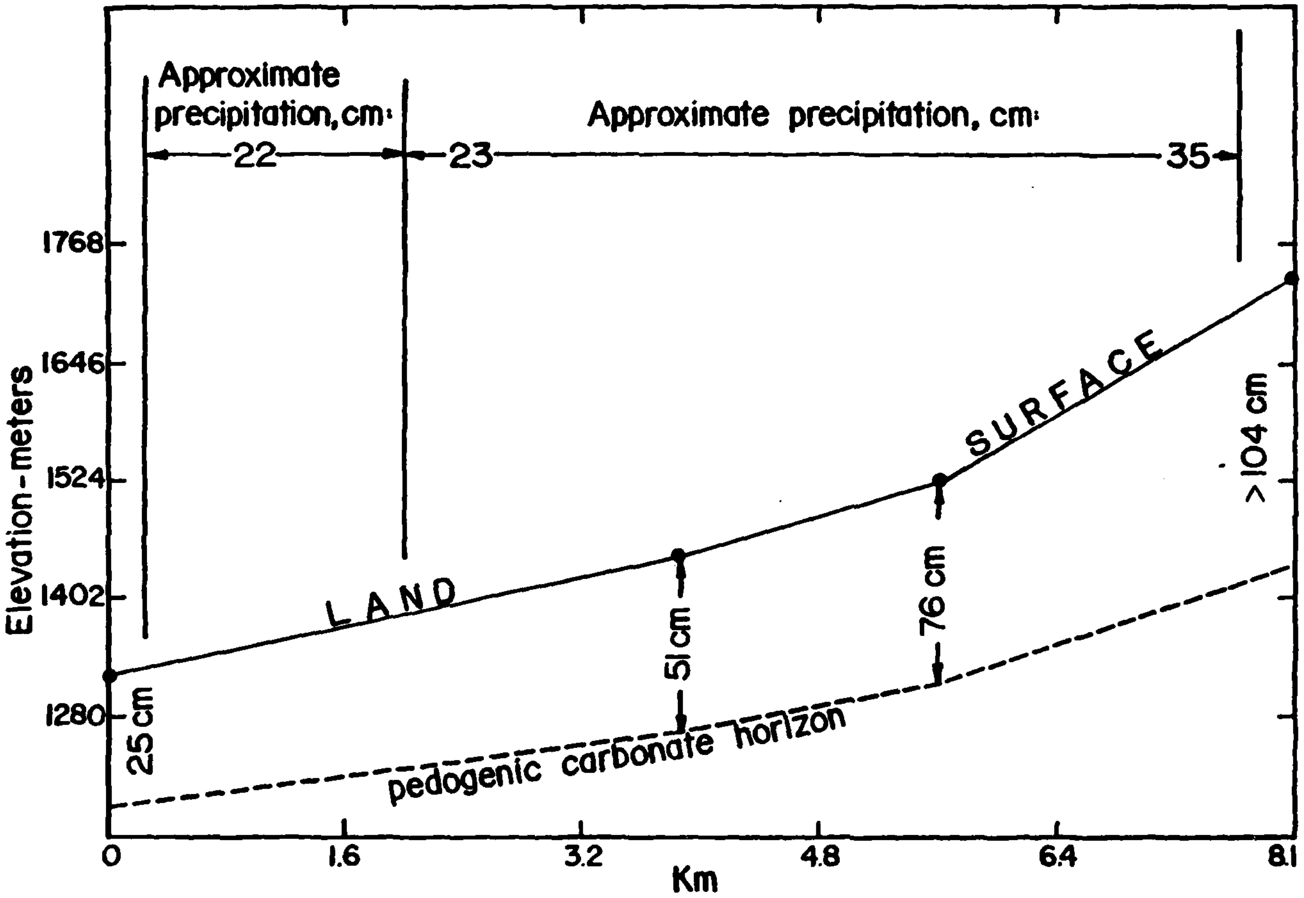



Figure 22. Relationship between precipitation, elevation and depth to pedogenic carbonate horizon (after Gile and Grossman, 1979).

Table 14. Spearman rank correlation coefficient for mean annual precipitation and depth to pedogenic carbonate horizon.

X = Mean annual precipitation
Y = Depth to $CaCO_3$ horizon
N = 24

| | | RANK | | | |
|---|---|---|---|---|---|
| X | Y | X | Y | $d_i$ | $d_i^2$ |
| 5.09 | 5.68 | 3 | 1 | 2 | 4 |
| 4.67 | 6.81 | 2 | 2 | 0 | 0 |
| 5.68 | 8.68 | 5 | 3 | 2 | 4 |
| 5.10 | 9.82 | 4 | 6 | -2 | 4 |
| 6.67 | 9.91 | 8 | 7 | 1 | 1 |
| 8.09 | 10.01 | 10 | 8 | 2 | 4 |
| 9.02 | 9.82 | 12 | 5 | 7 | 49 |
| 8.98 | 8.86 | 11 | 4 | 7 | 49 |
| 12.67 | 10.94 | 18 | 9 | 9 | 81 |
| 7.93 | 13.85 | 9 | 11 | -2 | 4 |
| 6.33 | 12.96 | 7 | 10 | -3 | 9 |
| 4.49 | 13.99 | 1 | 12 | -11 | 121 |
| 6.30 | 15.99 | 6 | 13 | -7 | 49 |
| 9.63 | 17.12 | 14 | 14 | 0 | 0 |
| 16.84 | 17.13 | 22 | 15 | 7 | 49 |
| 9.75 | 19.98 | 15 | 16 | -1 | 1 |
| 9.17 | 21.12 | 13 | 18 | -5 | 25 |
| 9.95 | 21.09 | 16 | 17 | -1 | 1 |
| 18.89 | 21.19 | 23 | 19 | 4 | 16 |
| 11.60 | 23.09 | 17 | 20 | -3 | 9 |
| 13.91 | 26.02 | 19 | 21 | -2 | 4 |
| 15.57 | 32.00 | 20 | 22 | -2 | 4 |
| 18.95 | 38.07 | 24 | 23 | 1 | 1 |
| 16.11 | 45.21 | 21 | 24 | -3 | 9 |

TOTAL $d_i^2 = 498$

$$r_s = 1 - \frac{[6\xi\, d_i^2]}{N^3 - N} \quad \text{then } r_s = 1 - \left[\frac{2988}{(13824 - 24)}\right] = 1 - .22$$

$$r_s = 0.78$$

Critical values of $r_s$ , where N = 24, at $\alpha = 0.01$: 0.485.

Thus $r_s > 0.485$ and is significant at the 0.01 level.

relationships between these two variables show that with increasing moisture, calcium carbonate is leached deeper into the alluvium. Data collected during the present study from soil profiles in Arizona and New Mexico follow these relationships (Figure 23; Table 14).

Parent Material

The size and sorting of alluvium is an important factor controlling the degree of calicum carbonate cementation (Gile and Grossman, 1979; Lattman, 1971 and 1973). Coarser grained materials have better developed caliche layers. It is observed that $CaCO_3$ accumulates more readily on larger clasts, although the detailed mechanics are not fully understood. Additionally, poorly sorted materials have better caliche development as there is less pore space, or void space, to fill with calcium carbonate.

Numerous investigators have determined that the composition of the alluvial parent materials is important in controlling the degree of cementation. Parent material of high carbonate composition, such as limestones, develop caliche horizons at a faster rate than low-carbonate parent material (Gile and Grossman, 1979). However, in desert basins of the southwestern United States, certain types of low-carbonate parent material have extensive amounts of pedogenic carbonate deposits. Specifically, parent material composed of clasts of basic igneous rocks (eg. basalts) have been observed with massive caliche horizons (Fig. 24). Lattman (1975) suggested that the release of calcium from the weathering of calcic-rich feldspars

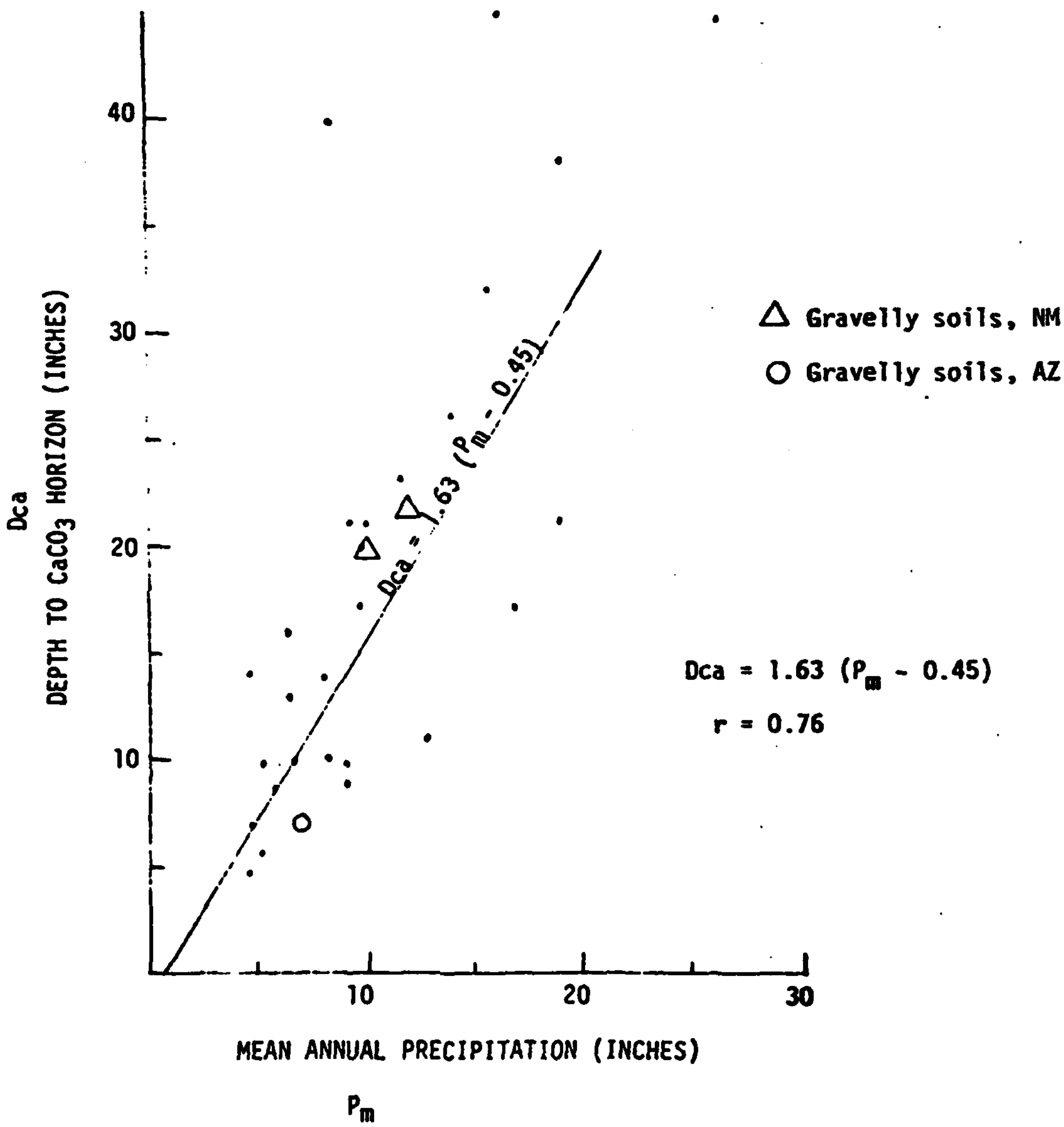



Figure 23. Relationship between mean annual precepitation and depth to pedogenic caliche horizon (after Arkley, 1963).

Figure 24. Calcium carbonate accumulation on basalt clasts and detritus in Nevada.

resulted in indurated caliche horizons in basaltic detritus; however, weathering studies conducted during this project indicates that such weathering would be overshadowed by atmospheric contributions of calcium carbonate (see Appendix B).

Figure 25 illustrates the relationship between parent material composition and the amount of pedogenic carbonate. Note that parent material with basic igneous and limestone compositions have the greatest pedogenic calcium carbonate content while mixed and acid igneous lithologies have the least. These values are typical for most well-developed caliche horizons in the southwestern United States. The low amounts of calcium carbonate in caliches developed in acid igneous rocks as compared to basic igneous rocks is illustrated in Figure 26. In addition, the distribution of petrocalcic horizons developed on low-carbonate parent material shows a marked difference between basic and acid igneous rocks. Terrains with extensive outcrops of basic igneous rocks have extensive petrocalcic horizons; whereas, areas of acid igneous (and metamorphic rocks) have a paucity of well-developed caliche (Fig. 27). A control basin in southwestern Arizona was selected where parent material of acid and basic igneous rocks were juxtaposed, and the geomorphic surfaces were of similar elevation. At this locality, the basic igneous rocks had better developed caliche, than the acid igneous parent material.Since the atmospheric contribution of calcium carbonate should be equal in such a small area (see Section 3) then some other factor related to the composition of the parent material must affect the solubility and precipitation of calcium

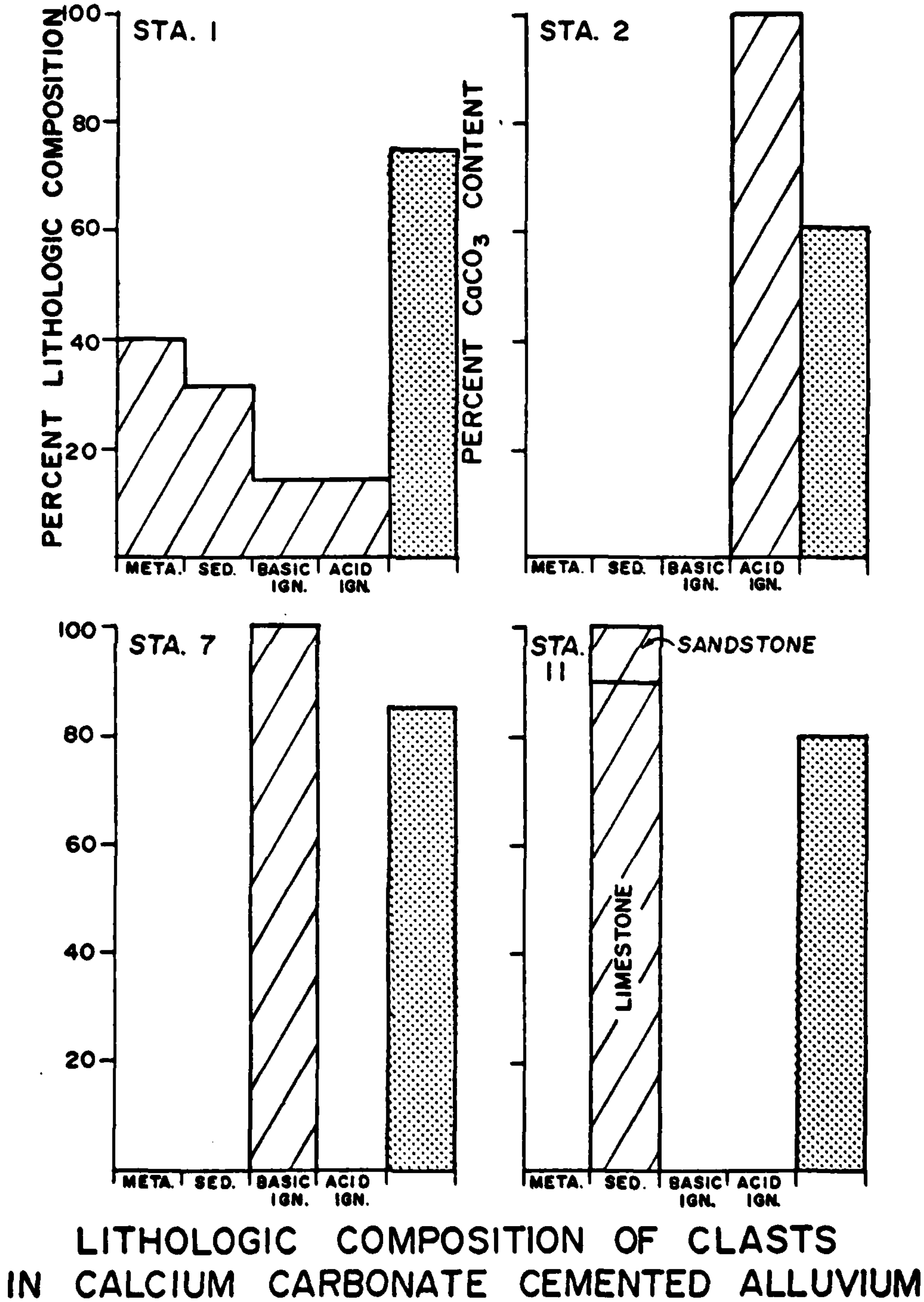



Figure 25. Relationship between parent material composition and the amount of calcium carbonate matrix in pedogenic càliches.

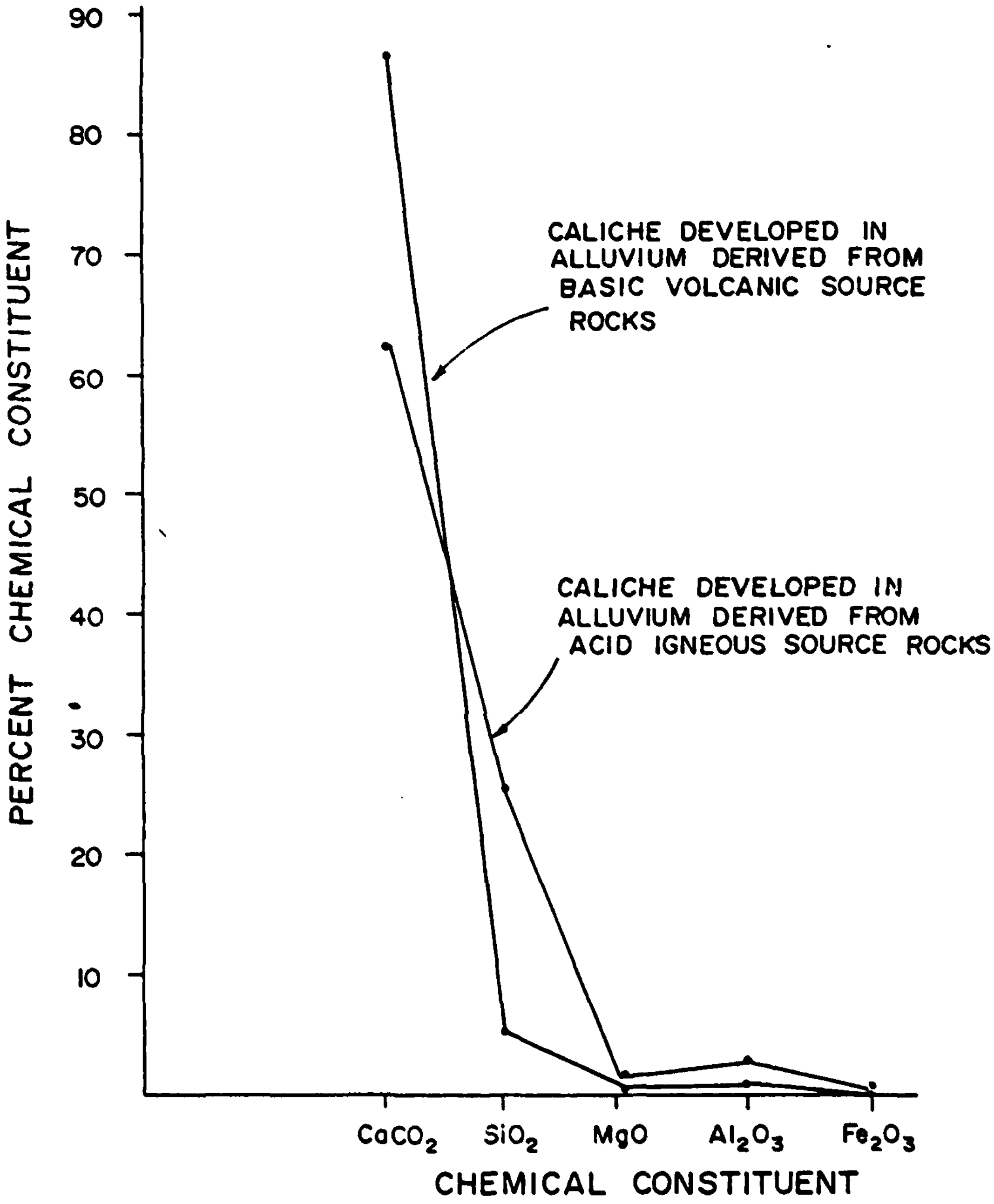



Figure 26. Comparison of chemical constituents in caliche developed on acid and basic igneous parent material.

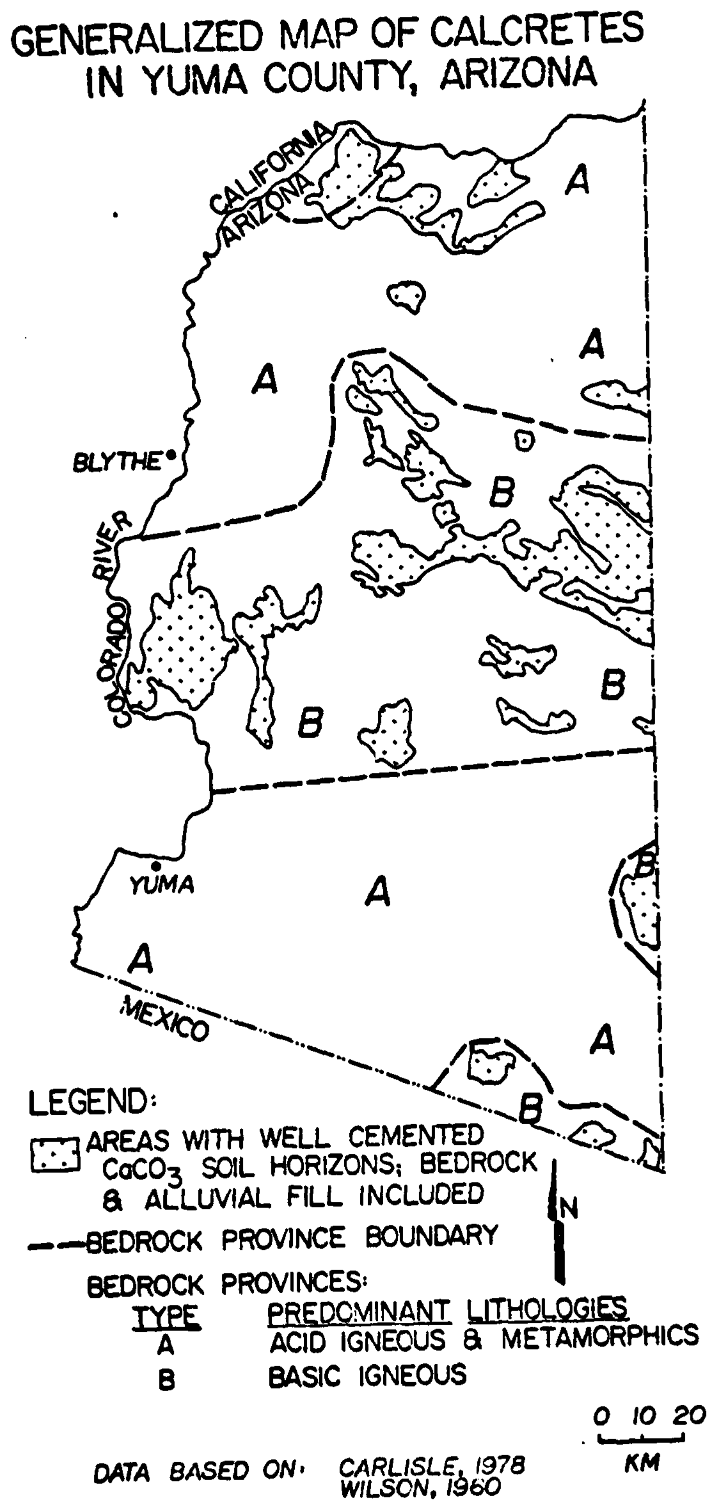



Figure 27. Map showing well-developed pedogenic caliche in bedrock provinces of southwestern Arizona.

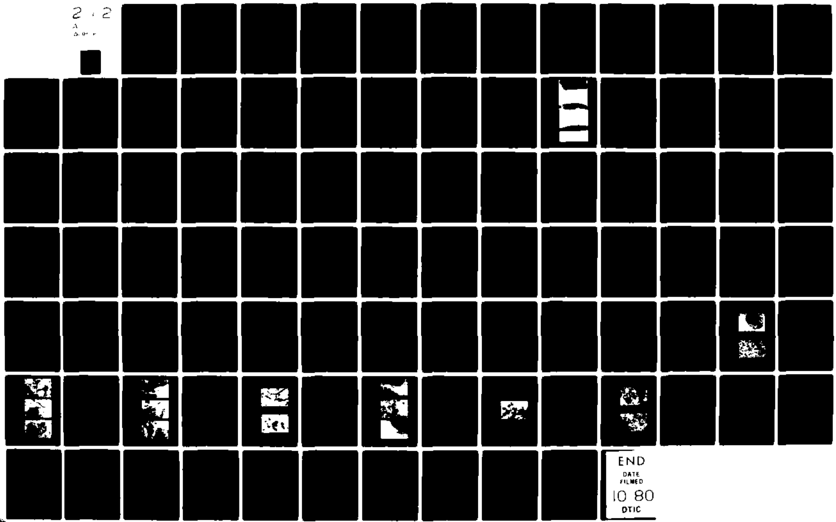
carbonate in the soil horizon.

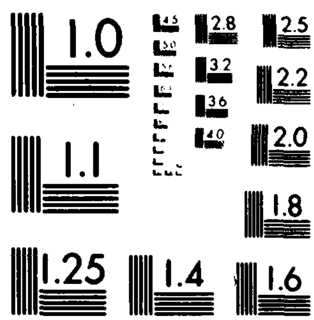
One of the major factors influencing calcium carbonate solubility is temperature. Increasing temperature decreases the solubility of calcium carbonate in the soil solution and precipitation is likely to occur. Field measurements of the surface temperature of basic and acid igneous rocks show typical diurnal variations; however, the peak temperature, which occurs in the afternoon, is greater on basic igneous rocks than on acid igneous rocks (Fig. 28). Differences in the thermal behavior of acid and basic igneous rocks are related to the thermal properties of the parent material (Table 15). Thermal capacity, the ability to store heat in parent material, is higher in basalts than in granite. Additionally, the ability to transfer heat from the surface of the material (thermal diffufusivity) and the rate of transfer (thermal conductivity) is lower for basic igneous rocks compared to acid igneous. All these conditions result in higher peak afternoon temperatures in basic igneous rocks. Such times of the day are when precipitation is most likely to occur (summer season). Thus, any rainfall during this time would carry calcium carbonate to the hot ground surface where the solubility of the solution would be decreased.

In order to quantitatively evaluate the difference in solubility of soil solutions in acid and basic igneous parent material, a plot of solubility versus temperature is constructed (Fig. 29). The difference in solubility at the maximum temperatures on these two different parent material is 0.13 g 1. The

AD-A089 621   NEW MEXICO UNIV ALBUQUERQUE DEPT OF GEOLOGY   F/G 8/13
PROPERTIES AND PREDICTION OF CALICHE IN ALLUVIAL BASINS OF THE --ETC(U)
JUL 80   S G WELLS, J D SCHULTZ   AFOSR-78-3572
UNCLASSIFIED   AFOSR-TR-80-0747   NL

2 of 2






MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

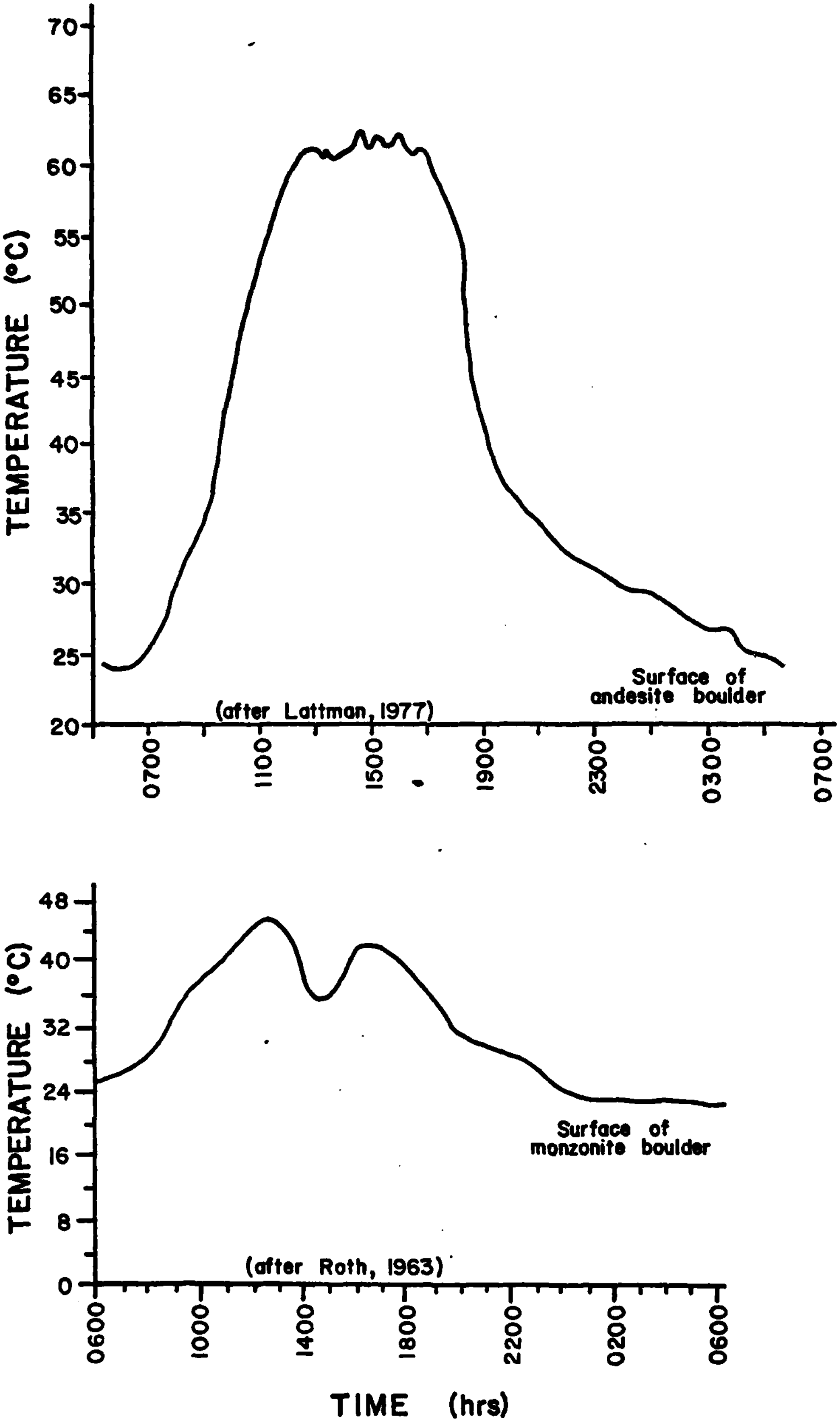



Figure 28. Diurnal temperature fluctuations on basic and acid igneous rocks in desert alluvial. Measurements were conducted in the field.

Table 15. Thermal properties of three major rock types.

## TYPICAL THERMAL PROPERTIES OF SELECTED ROCK TYPES

| ROCK TYPE | C<br>THERMAL CAPACITY<br>(cal)/gm(°C) | k<br>THERMAL DIFFUSIVITY<br>$cm^2$/sec | K<br>THERMAL CONDUCTIVITY<br>cal/cm (sec)(°C) |
|---|---|---|---|
| BASALT | 0.20 | 0.009 | 0.0050 |
| GRANITE | 0.16 | 0.016 | 0.0070 |
| LIMESTONE | 0.17 | 0.011 | 0.0048 |

C, THERMAL CAPACITY : ability of material to store heat

k, THERMAL DIFFUSIVITY : ability of material to transfer heat to and from the surface of the material

K, THERMAL CONDUCTIVITY: measure of rate of heat transfer through material

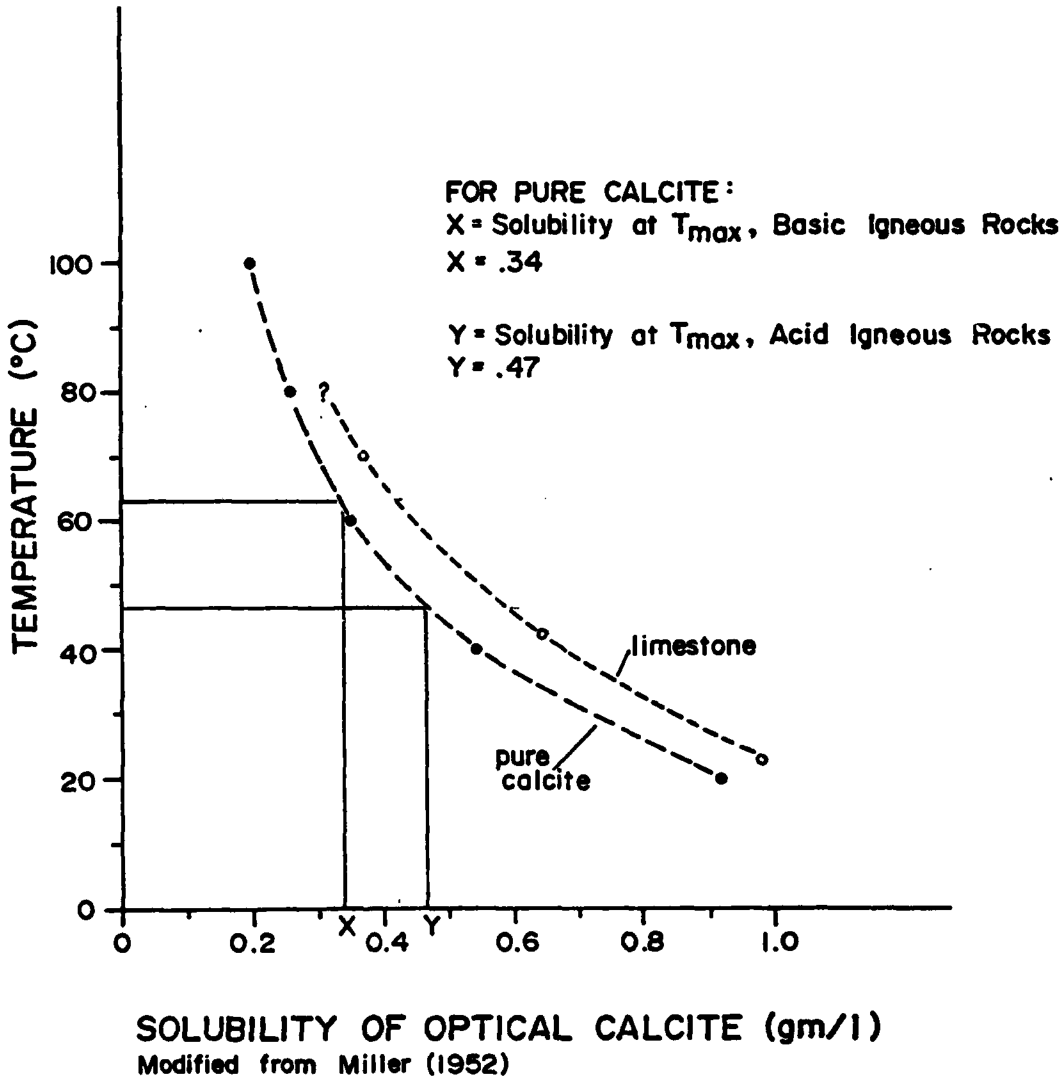



Figure 29. Solubility of calcite as a function of temperature. Note solubility differneces for temperatures of two different parent materials.

lower solubility on the basic igneous rock, 0.34 g/l, allows precipitation of the calcium carbonate more readily than the acid igneous rocks. Differences in solubility between the different parent material change with depth in the soil horizon as the temperatures change with soil depth (Fig. 30). The upper 10 cm of soil horizon is the zone where the solubility differences are the highest, and below this depth the difference is relatively small.

This study indicates that extensive caliche deposits on basic-- igneous parent material are related to the thermal properties of the parent material which from $CaCO_3$ precipitation. Additional amounts of calcium are provided by weathering of feldspar minerals; however, this contribution is small when compared to the volume supplied from the atmosphere.

## Land Surface Stability

The relative stability of a landscape is important to calcium carbonate accumulation and soil formation. Surfaces undergoing rapid erosion and deposition are not stable enough for pedogenic processes to be operative. A surface must remain stable over long periods of time to allow soil formation and calcium carbonate accumulation. Surfaces must remain stable for several 100,000 yrs. before Stage IV caliches can evolve or even 10,000 yr for Stage I caliches to form. As mentioned in the section 1, older landscape units will have the most well-developed caliches, provided the surface is not buried or dissected.

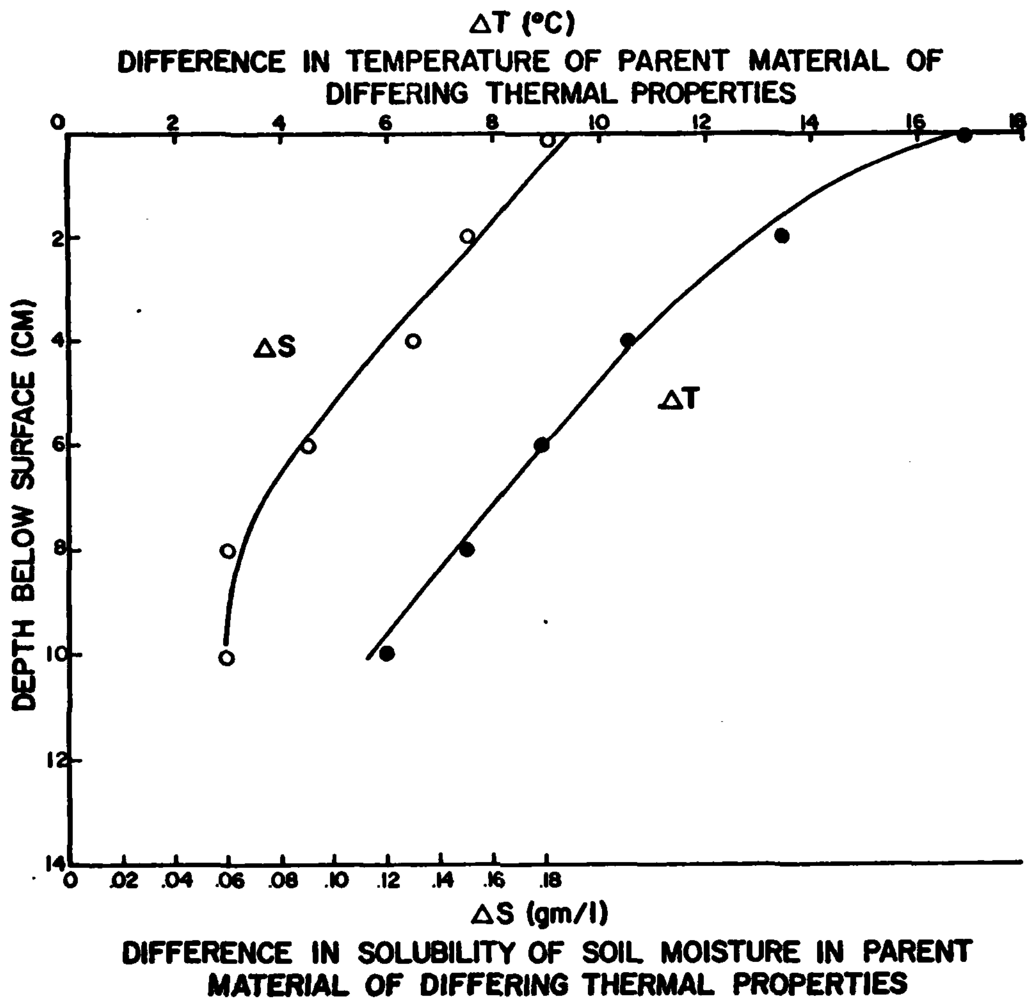



Figure 30. Changes in solubility and temperature differences with soil-profile depth in parent materials which differ in thermal properties.

Variables which tend to increase calcium carbonate accumulation, such as the availibility of $CaCO_3$ fines or high-carbonate parent material, are less important if active deposition or erosion is taking place. For instance, the eastern side of the Tularosa basin in southern New Mexico is downwind from a high-calcium source area. Thus, one would expect well developed caliche horizons on these west facing piedmonts. However, little pedogenic cementation occurs due to the recent tectonic activity along the mountain front and the rapid deposition of alluvial fans on the valley piedmont.

Surface stability is less important to the development of non-pedogenic caliche, such as certain types of laminar layers and case-hardening.

## Summary

Although numerous factors influence the development of soils, three basic conditions exist which favor the rapid accumulation of pedogenic carbonate:

1) availibility of $CaCO_3$ in the atmosphere or parent material;
2) thermal properties and texture of the parent materials;
3) age and stability of geomorphic surface developed on parent material.

If all three conditions are favorable, then extensive and well-developed caliche horizons will develop.

# 7. METHODS OF PREDICTING PEDOGENIC CALICHE OCCURRENCE AND DISTRIBUTION IN ALLUVIAL BASINS

The distribution of pedogenic carbonate deposits in alluvial basins of southwestern United States can be determined from detailed soil maps of the Soil Conservation Service (U. S. Department of Agriculture). However, many alluvial basins have not been mapped in detail or mapped at all, and little is known about the distribution of carbonate-rich soils. The purpose of the following sections is to provide data concerning the distribution of caliche in alluvial basins and to provide methods of predicting caliche occurrence and development in unmapped regions.

Previous studies on determining the distribution of caliche (Carlisle, 1978) and on predicting the occurrence of desert soils (Gile and Hawley, 1972) provide base-line data and previously applied techniques. Gile and Hawley (1972) considered factors such as topography, parent materials, soil age and climate in prediciting desert soil occurrences. They recommended the use of aerial photgraphy, geologic maps, topographic maps and hydrologic data as tools for soil predicition. To compliment their study, the present investigation was aimed toward developing semi-quantitative field and lab criteria for predicting the occurrence and degree of pedogenic caliche in a variety of alluvial basins.

## Regional Caliche Maps

Maps delineating regions in alluvial basins most likely to contain pedogenic caliche were constructed from previous data bases, techniques suggested by Gile and Hawley, and procedures developed during the present study. The primary purpose of these maps is to delineate areas of alluvial basins which have a high probability of containing near-surface pedogenic caliche. Each maps is constructed at a scale of 1:250,000 covering the same area as the U. S. Geological Survey $2^{o}$ topographic sheets; thus, these maps can be superimposed on the $2^{o}$ topographic sheets to locate cultural features, valley and mountain boundaries, and elevation. The $2^{o}$ topographic sheets covered by these maps include Kingman, Needles, Salton Sea, El Centro, Phoenix, Ajo and Lukeville. These maps are given on Plates I through VII and cover portions of southern California, southern and western Arizona, and southern Nevada.

Data used to construct these maps (Plates I VII) include:

1) maps published by the Soil Conservation Service;

2) a map published by Carlisle (1978);

3) selected aerial photography and satellite imagery;

4) and field investigations.

On each map, only the alluvial basins were mapped. Bedrock outcrops and mountain ranges were not included in that the primary siting for the MX Systems. alluvial valleys. The boundaries delineating regions likely to contain pedogenic from those without caliche are transitional. In addition, areas mapped as caliche-bearing may include smaller areas with little clacium carbonate cementation, or may contain nonpedogenic caliche.

Maps given on Plates I through VII serve as a regional guide to the distribution of pedogenic caliche. In the following section, detailed criteria for delineating the occurrence and stage of development of pedogenic caliche is discussed. This criteria can be applied to any single alluvial basin represented on Plates I through VII to predict caliche occurrence and degree of cementation.

## Field and Map Criteria for Predicting Pedogenic Caliche Occurrence and Degree of Cementation

Three basic conditions exist which influence the accumulation of pedogenic carbonate in alluvial basins:

1) availibility of calcium from the atmosphere or from parent material;
2) and the textural and thermal properties of the parent materials;
3) and the age and stability of the geomorphic surface upon which caliche develops and is preserved.

Field criteria reflecting the relative importance of each factor provides several methods of determining both the caliche occurrence and its degree of cementation. This field criteria can be used in conjunction with geologic maps, aerial photography and satellite imagery.

Availibility of $CaCO_3$:

The atmospheric contribution of calcium to the land surface has been determined to be 2 $g/m^2/yr$ and has been determined to be relatively uniform over the southwestern United States (Gile and Grossman, 1979; Junge and Werby, 1958) (Fig. 31). However, areas

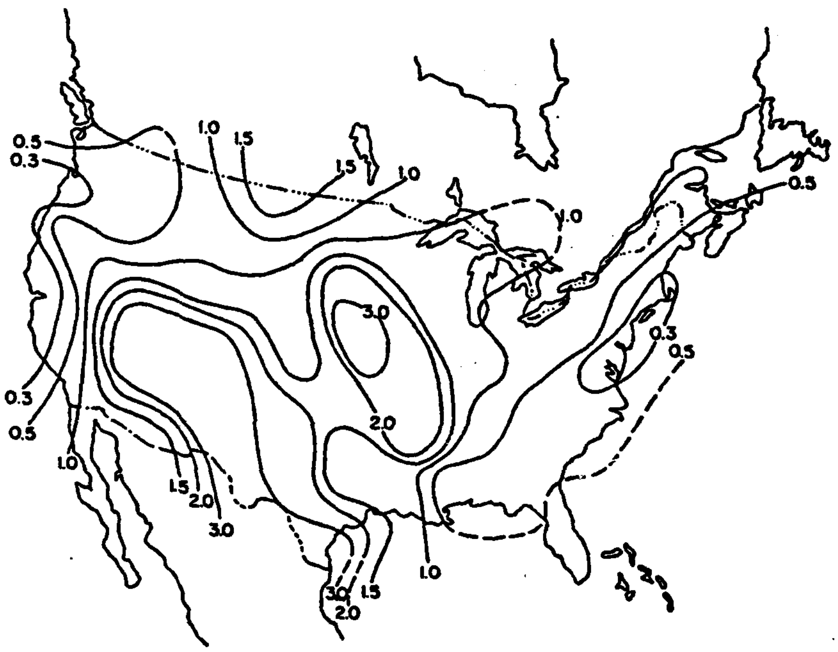



Figure 31. Average calcium concentration (mg/l) in rainwater over continental United States (after Junge and Werby, 1958).

subjected to dust storms will have the highest concentrations of calcium ions in the atmosphere. A feedback condition exists between the land surface and the atmosphere whereby calcium ions are re-circulated. Areas on the land surface which have concentrations of fine particulate matter and little vegetation provide ready-sources of calcium ions for eolian transport into the atmosphere. Certain physiographic areas receive runoff carrying dissolved calcium, and upon drying calcium-rich dust is available. These areas are typically in the axes of alluvial basins and include playas or shallow, broad washes. Areas most likely to receive this eolian-transported calcium are regions undergoing eolian deposition. These areas include land surfaces downwind from playas, broad washes, extensive dune deposits, and areas underlain by eolian deposits. Areas subjected to eolian erosion and deposition provide a continuous circulation of calcium-rich dust between the land surface and atmosphere.

Alluvial material downwind from carbonate-rich sediment are characterized by well-indurated pedogenic caliche (Purcell, 1973; Wells, 1976). Alluvial basins which have closed drainage or have little basin-axis dissection accumulated calcium-rich fines in the center of the basin. The amount of eolian deposition and calcium carbonate concentration in the eolian fines decreased linearly from the source areas (Fig. 32). Eolian deposits contain concentrations of calcium carbonate of 5 to 10 percent as far as 600 m from playa sources and at depths of 2.5 cm beneath the surface. Most of the carbonate-rich dust occurs in grain sizes less than 0.0625 mm.

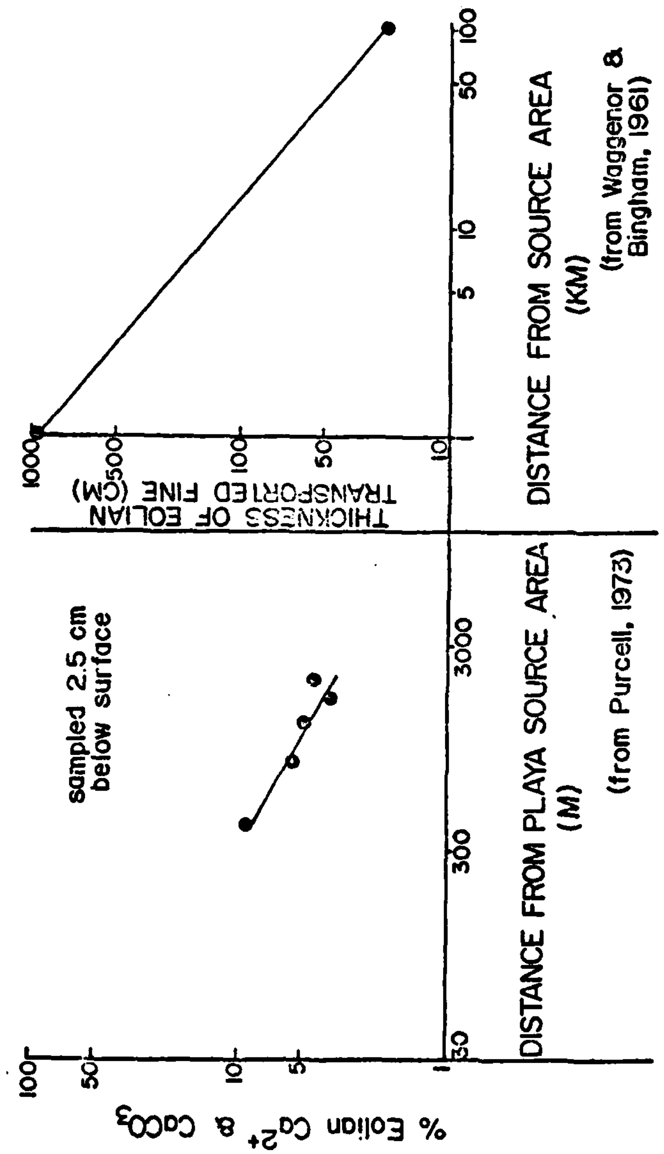



Figure 32. Changes in thickness and $CaCO_3$ content in eolian deposits with distance from $CaCO_3$ source area

Parent materials provide calcium carbonate by weathering processes on individual clasts in the alluvium or on bedrock outcrops. a heirarchy of parent material lithologies which reflect the relative availibility of calcium and the degree of carbonate cementation is given in Table 16. Parent materials composed of limestone and basic igneous clasts have the best developed and most extensive pedogenic carbonate deposits. Acid igneous clasts have the least developed and least extensive caliche.

Alluvium composed of limestone and basic igneous clasts may have as much as 20 percent more calcium carbonate matrix for a given soil age than acid igneous rocks (Fig. 25). Additionally, areas in which the bedrock is dominantly carbonate or basic igneous will have 2 to 3 times more extensive pedogenic caliche (Fig. 27). Delineating bedrock lithologies in mountain ranges surrounding the alluvial basins and using the heirarcy in Table 16 provide a tool to predict the degree of development and extent of pedogenic caliche.

## Textural and Thermal Properties

All other conditions constant, parent materials of coarse grained alluvium has better developed caliche (thicker and more indurated) than fine grained alluvium (Gile and Grossman, 1979). The prediction of grain size distribution in desert alluvial basins has been investigated by Dr. William Bull of the University of Arizona. Utilization of the results from this study will aid in predicting the distribution and development of caliche. Field observations conducted during this investigation indicate that alluvium composed

Table 16. Relationship between parent material composition and development of pedogenic caliche.

| PARENT MATERIAL COMPOSITION | | DEVELOPMENT AND EXTENT OF PEDOGENIC CALICHE |
|---|---|---|
| Carbonates: | limestone | high |
| | dolomite | high |
| Basic igneous | | high |
| Gypsum | | moderate |
| Metamorphic: | high carbonate | moderate |
| | low carbonate | low |
| Acid Igneous | | low |

of granite and clastic sedimentary lithologies have greater concentrations of smaller clasts. In granite detritus, commonly 50 percent (by weight) is less than 4 mm; whereas, in basalt and andesite 50 percent (by weight) is greater than 4 mm. Textural measurements in the field support these observations (Appendix E). The larger grain sizes of the more basic igneous clasts would promote the accumulation of calcium carbonate at a faster rate than the finer grained granitic detritus.

In addition to the textural properties, this investigation has shown that the thermal properties promote rapid calcium carbonate accumulation in alluvium composed of basic igneous detritus. Higher maxiumum temperatures on basic igneous clasts results from lower thermal capacity, lower thermal diffusivity and higher thermal capacity (Table 15). The effect of higher temperatures on calcium-rich solutions seeping through the soil is to reduce the solubility and promote precipitation (Fig. 29). Thus, in areas of low-carbonate parent material extensive and well-developed caliche horizons may be predicted if the parent material is basic igneous in composition (Fig. 27).

Age and Stability of Geomorphic Surfaces:

The other major factor affecting the occurrence and development of pedogenic calcium carbonate horizons is the age of the soil (or the age of the geomorphic surface upon which the soil occurs) and the stability of the land surface. Field and map criteria used to evaluate the relative stability and age of geomorphic surfaces (and thus soil ages) provides a reliable method of predicting caliche occurrence and development. This field and map criteria includes:

1) relative topographic position of geomorphic surface;
2) relative amount of dissection of geomorphic surface;
3) relative amount of depostion on geomorphic surface;
4) degree of desert pavement development on surface;
5) and, degree of desert varnish development on clasts at surface.

Each of these variables provide clues to the age and stability of the land surface which provides information concerning the soil age. In section 4 it was demonstrated that calcium carbonate extent (areal and depth) and induration increases with soil age. Older soils will have the most extensive and most indurated caliche horizons, and younger soils will have the least caliche.

The relative topographic position of a geomorphic surface along the piedmonts of alluvial basins commonly reflect the relative age of the surface: oldest - highest, intermediate - next oldest, and lowest - youngest. Recent dating techniques by Ku _et al_ (1979) have quantitified the ages for these positions on piedmont surfaces of coutheastern California (Fig. 21). From this information we can see the following relationship between the soil age, or degree of caliche development, and topographic position of geomorphic surface:

low surfaces - Stage I to II development
intermediate surface - Stage II to III development
high surfaces - Stage III to IV development

The areal extent of the caliche deposits as well as the age, is function of the stability of the geomorphic surface. Instability is indicated by rapid erosion of deposition. The relative amount of erosion and deposition can be determined from measurable map parameters. The relative amount of erosion on a geomorphic surface is defined as dissection. Dissection describes the depth and areal extent of downcutting by streams. In section 5 relationship between drainage frequency and caliche was illustrated; however, a better measure of dissection (indicating both depth and extent) is drainage texture. A drainage texture map was constructed of an alluvial basin in Study Area A and is given in Plate IX. Instructions on the construction of this map is given in Appendix F. A comparison of Plate IX with Figure 33 illustrates that areas of extreme dissection have little caliche preserved. The map units in Figure 33 which have extensive caliche deposits are Qcr, Qvr and portions of Qfc. Areas with 10 km of eroding channels per $km^2$ do not have areally extensive deposits. Likewise, areas of 2 km of eroding channels and less have little caliche deposits near the surface. These areas are undergoing deposition rather than erosion. Map units on Figure 33 which reflect recent deposition include Qff and Qds. These units occur in areas with less than 2 km of eroding channel per km. Additionally, a comparison of generalized soil map of the study basin (Fig. 34) with Plate IX shows that young soils with little caliche (unit T on map) occur in areas with extremely low drainage texture units. These portions of drainage basins commonly have low slopes and therefore receive sediments eroded from the mountains and piedmonts. Plate X illustrates the slope conditions on the study basin, and a

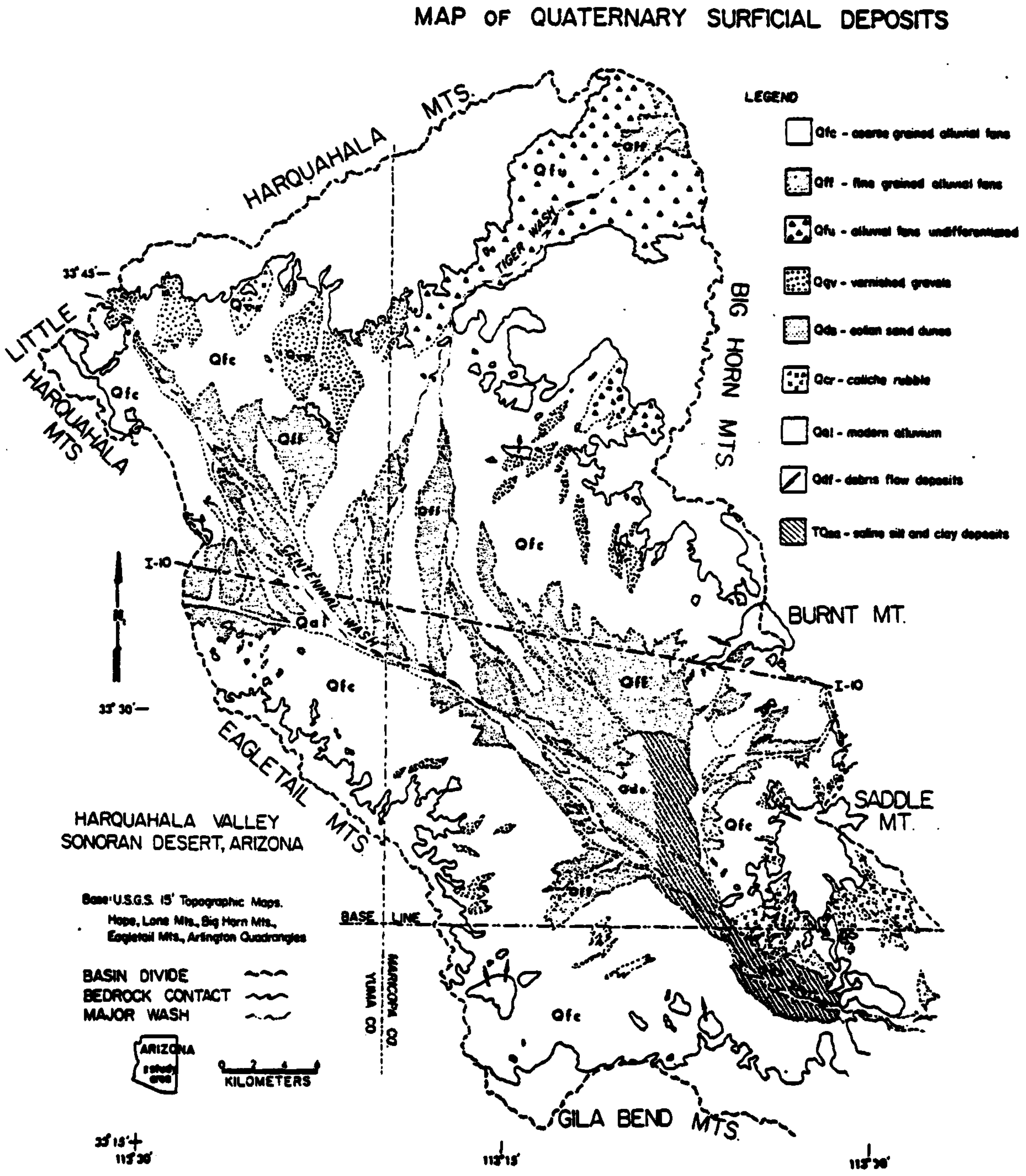



**Figure 33. Map of Quaternary surficial deposits in alluvial basin of study area A.**

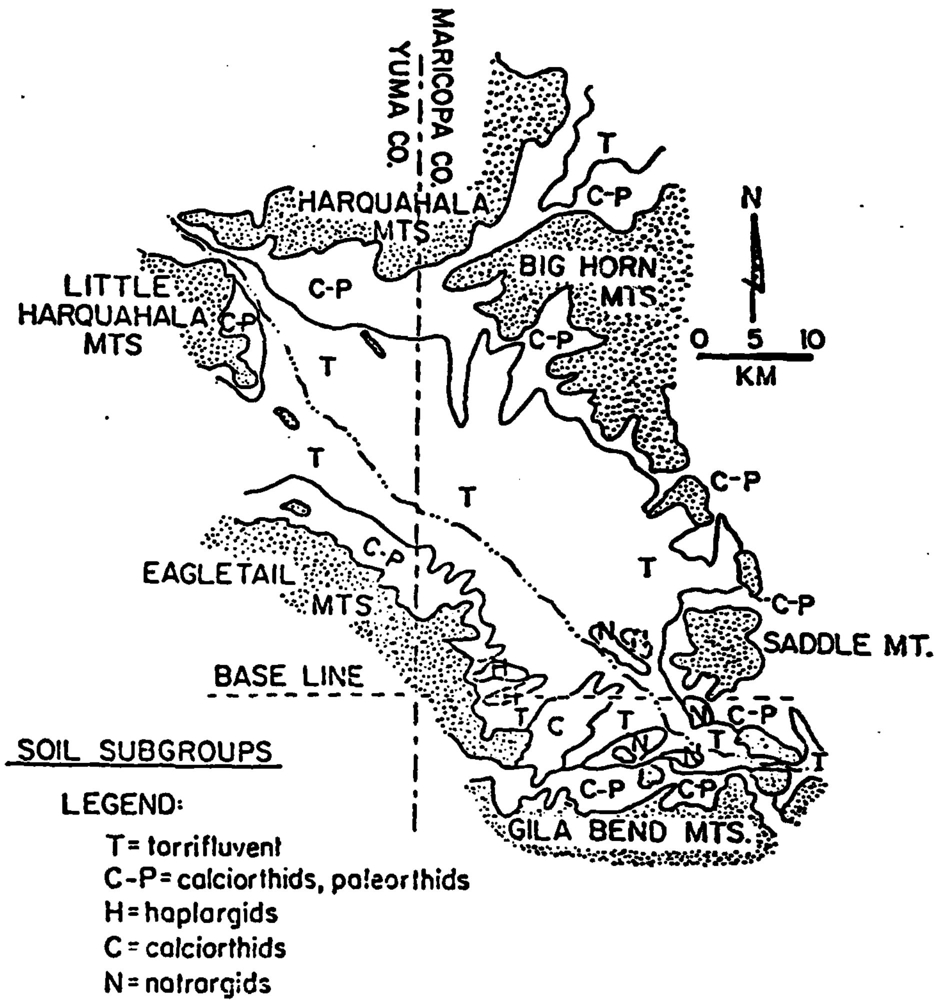



Figure 34. Generalized map of soil types in alluvial basin of study area A. Units C, C-P and H have pedogenic caliche deposits.

comparison of this plate with Figure 34 indicates that slopes angles of $0.75^{\circ}$ and less have very young soils and very little pedogenic caliche.

Two other surface conditions reflect the age and stability of the land surface: (1) desert pavement and (2) desert varnish. Desert pavements are armored surfaces of angular or rounded clasts which are only one or two clasts thick and rest on a thin layer of silt. Well-developed desert pavements (high stone concentrations or complete armor) reflect older and stable surfaces under which caliche would form and be preserved. Additionally, desert varnish, (patina) on the exposed portions of the clasts, indicates the relative age. The older the geomorphic surface and the more desert varnish causes surfaces to be darker with age.

Geomorphic surfaces which have extensive, well-developed desert pavement and a dark coating of desert varnish on the surface are relatively older therefore are likely to have well-developed pedogenic caliche. Younger surfaces with little caliche have little to no pavement and little to no varnish on the clasts.

Figure 35 illustrates some of these surface-soil age relationships. Figure -35a is a young surface undergoing deposition. It is relatively undissected, has slope angles less than $0.5^{\circ}$ and occurs in the basin axis. Such surfaces have Stage I or less of pedogenic caliche. Figure 35b is a low intermediate surface with coarse clasts. Little desert pavement and light desert varnish on the clasts suggest a moderately youthful age. Stage I to perhaps Stage II caliche development might be associated with such a surface.

Figure 35a. Young geomorphic surface undergoing active deposition; no caliche deposits of pedogenic origin are present.

Figure 35b. Intermediate level geomorphic surface with Stage I to II caliche development.

Figure 35c. High level geomorphic surface with desert pavement and varnish; Stage III to IV of pedogenic caliche is common.

Finally, Figure 35c is a upper-intermediate to upper surface with a well developed desert pavement and a thick desert varnish. These surfaces are older and more stable and have Stage III to IV caliche development.

## Summary

Table 17 summarizes the major criteria for predicting the occurrence, degree of development, and relative extent of pedogenic caliche in desert alluvial basins of the Basin and Range Province. The land surface conditions can be observed in the field, from aerial photography, and from topographic maps. Parent material conditions can be obtained from field observations, from aerial photography or imagery, and from published geologic maps.

## Evaluation of Satellite Imagery for Subaerial and Buried Caliche - Detection

Buried caliches are common on geomorphic surfaces which are old and stable. Surfaces with desert pavements and varnish are relatively stable and old. Such surfaces are very dark thus are visible on aerial photography and imagery.

Erosional processes in alluvial basins may expose previously buried caliche horizons. Caliche horizons on such erosional surfaces may be subjected to mechanical breakup and may develop a thin layer of caliche rubble and silt. Since caliche is white to light buff in color, alluvial material containing caliche should have lighter tones. Caliche when exposed to the surface has a dramatic effect on

Table 17. Relationships between factors influencing $CaCO_3$ accumulation in soil and the degree of $CaCO_3$ horizon development.

| Pedogenic Caliche Stage | I | II | III | IV |
|---|---|---|---|---|
| Geomorphic Surface Conditions | -relatively low topographic level of surface | -intermediate to low level of surfaces | -intermediate to high topographic level of surfaces | - high topographic level of surfaces |
| | -very low slope angles | - slope angles of $0.5^{o}$ to $2^{o}$ | - slope angles greater than $1.5^{o}$ | - slope angles greater than $2^{o}$ |
| | -little dissection | - little dissection | -moderate dissection | - moderate to high dissection |
| | -no pavement or varnish | - little pavement, slight varnish | -well-developed pavement, moderate varnish cover | -well-developed pavement and dark, thick varnish |
| | -imagery densities = 0.2 to 0.5 | -imagery densities = 0.35 to 0.5 | -imagery densities = 0.4 and greater | -imagery densities = 0.6 and greater |

| Degree of Caliche Development and Extent | Local-Weakly Cemented | Slightly Indurated Moderately Extensive | Well Indurated Regionally Extensive |
|---|---|---|---|
| Parent Material Conditions | -low carbonate parent material (acid ign. or metamorphic) | -moderate carbonate content in parent material (gypsum) | -high carbonate content (limestone) or basic ign. clasts |
| | -fine grained parent material | -mixed fine and coarse but skewed toward fines | -coarse grained parent material |

the landscape morphology as described in section 5. Both of these variables, light-tonal appearance and geomorphic effect, enhance the use of satellite, or airborne, imagery for caliche detection.

Recent studies of the southwestern United States have found aerial imagery to be a useful tool for identifying calichified alluvial surfaces in Nevada basins (Lattman, 1971; Lenhart, 1974). Lenhart (1974) used two techniques, the ratio and contrast methods, to quantitatively evaluate the differences in the density of calichified and non-calichified alluvial surfaces. He found the contrast method to be the optimum technique to separate these fan surfaces. Using a modified contrast method, density differences among various types of surficial deposits in study Basin A basins of Arizona were evaluated. The Arizona study differs from the Nevada study, in that multiple frames were used in Nevada as compared to single frame in Arizona. Additionally, both black and white MSS Band 7 and color infrared composites of Bands 4, 5, and 7 were used for the Arizona study as compared to the black and white Band 7 in Nevada.

The results of the imagery study for Arizona are given in Tables 18 and 19, and are described below:

1) The mean of the image density for both calichified and non-calichified surfaces are nearly the same, 0.67 and 0.69 respectively.
2) The variance of the image density for calicified surfaces is greater ($7.2 \times 10^3$). These results support the work in Nevada by Lenhart.

Table 18. Variance of image densities in basin of study area A, southwestern Arizona.

| | Calichified Surface | | | Non-Calichified Surface | | |
|---|---|---|---|---|---|---|
| | | $x_i - \bar{x}$ | $(x_i - \bar{x})^2 \times 10^3$ | | $x_i - \bar{x}$ | $(x_i - \bar{x})^2 \times 10^3$ |
| | 0.63 | -.04 | 1.6 | 0.66 | -0.03 | 0.9 |
| | 0.65 | -.02 | 0.4 | 0.65 | - .04 | 1.6 |
| | 0.60 | -.07 | 4.9 | 0.66 | - .03 | 0.9 |
| | 0.75 | .08 | 6.4 | 0.75 | .06 | 3.6 |
| | 0.89 | .22 | 48.4 | 0.63 | - .06 | 3.6 |
| | 0.67 | 0.00 | 0 | 0.67 | - .02 | 0.4 |
| | 0.93 | .26 | 67.6 | 0.61 | - .08 | 6.4 |
| | 0.63 | -.04 | 1.6 | 0.68 | - .01 | 0.1 |
| | 0.63 | -.04 | 1.6 | 0.81 | 0.12 | 14.4 |
| | 0.65 | -.02 | 0.4 | 0.71 | .02 | 0.4 |
| | 0.67 | 0 | 0 | 0.94 | .15 | 22.5 |
| | 0.68 | .01 | 0.1 | 0.72 | .03 | 0.9 |
| | 0.59 | -.08 | 6.4 | 0.61 | - .08 | 6.4 |
| | 0.64 | -.03 | 0.9 | 0.60 | - .09 | 8.1 |
| | 0.63 | -.04 | 1.6 | 0.67 | - .02 | 0.4 |
| | 0.65 | -.02 | .4 | 0.73 | .04 | 1.6 |
| | 0.75 | .08 | 6.4 | 0.71 | .02 | 0.4 |
| | 0.61 | -.06 | 3.6 | 0.63 | - .06 | 3.6 |
| | 0.63 | -.04 | 1.6 | 0.72 | .03 | 0.9 |
| | 0.68 | .01 | 0.1 | 0.66 | - .03 | 0.9 |
| | 0.67 | 0 | 0 | 0.70 | .01 | 0.1 |
| | 0.64 | -.03 | 0.9 | 0.70 | .01 | 0.1 |
| | 0.59 | -.08 | 6.4 | 0.65 | - .04 | 1.6 |
| Mean: | $\bar{X}$=.67 | | $\Sigma$=172.2 | $\bar{X}$=.69 | | $\Sigma$ 86.5 |

Variance: $\sigma^2 = 7.2 \times 10^{-3}$ $\qquad$ $\sigma^2 = 3.6 \times 10^{-3}$

Table 19. Density measurements from color composite transparencies of MSS bands 4, 5 and 7 of Landsat imagery of basins in study area A, Arizona.

| QUATERNARY SURFICIAL DEPOSIT | DENSITY MEASUREMENTS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Varnished gravels (Qgv) | 0.67 | 0.69 | 0.71 | 0.65 | 0.64 | 0.68 | 0.64 | 0.61 |
| Fine grained fans (Qff) | 0.43 | 0.39 | 0.40 | 0.34 | 0.37 | 0.38 | 0.38 | 0.31 |
| Coarse grained fans (Qfc) | 0.49 | 0.42 | 0.44 | 0.37 | 0.35 | 0.47 | 0.56 | 0.45 |
| Alluvium (Qal) | 0.19 | 0.27 | 0.30 | 0.43 | 0.30 | 0.48 | 0.30 | 0.28 |
| Caliche rubble (Qcr) | 0.45 | 0.50 | 0.34 | 0.33 | 0.35 | 0.33 | 0.37 | 0.63 |

3) Calichified surfaces are not statistically different from uncemented coarse grained alluvial fans. Lenhart (1974) was able to separate these deposits on fan surfaces in Nevada.

4) Calichified surfaces can be differentiated statistically based on image densities from fine grained alluvial fans and varnished gravels.

5) The morphology of exposed caliche (Stage III or IV) on satellite imagery is characteristically similar in Nevada and Arizona. Calichified surfaces appear as light-toned, finger-like ridges.

6) Buried pedogenic caliches are common on surfaces with pavements and gravels (Qgv in Fig. 33). Densities values measured on these surfaces are 0.60 and greater. They are statistically different from other types of surficial deposits.

Techniques developed for the detection of caliche distribution by satellite imagery were applied to alluvial basins in Study Area D in central Nevada. Results of this study are given in Plate VIII. Landsat imagery (color composite) was analyzed to detect the relative age of geomorphic surfaces. Field analysis of selected basins indicated that the mapping and predicting procedure was relatively successful. Active areas and low level surfaces contained little caliche, typically Stage I at the most. Intermediate levels contained Stage II and Stage III. Stage III was common to the high level surface. Stage IV development of caliche was rare and limited perhpas due to the active tectonism of these alluvial basins. Parent materials composed of dark clasts, such as the dark slates of the Monitor alluvial basin, indicate ages of geomorphic surface to be much older than they actually are when investigated in the field. Such problems can be accounted for if geologic maps of the mountain ranges indicate color of the parent material.

## CONCLUSIONS

Major conclusions of this study are listed below:

1) Several types of caliche deposits are typical of alluvial basins in the Basin and Range Province of the United States. Pedogenic caliche is the most regionally extensive and poses the greatest threat to the near-surface installation and NWE survivability fo the MX Systems. Well-indurated caliche, referred to as petrocalcic or Stage III - IV, have the greatest thickness and lateral continuity on the desert land surfaces.

2) The amount of calcium carbonate in soil horizons is the greatest factor affecting the physical properties of caliche. The amount of calcium carbonate in soil horizons increases with time. Tens of thousands of years are required to produce thick, indurated caliche; thus such soils are gelogically old features. Source of calcium and calcium carbonate for caliche development is from atmospheric contributions (eolian dust and rainfall) and is contributed to the land surface at a rate of 2 $g/m^2/yr$. Additional contributions are made from the weathering of calcium from parent materials.

3)Calcium carbonate cementation is distributed unevenly across alluvial basins. Well-indurated caliches occur on topographically higher geomorphic surfaces which are common near the margin of the mountain front. Weakly-cemented caliche is typical of the low slopes along basin axis where deposition is more frequent.

4) Compressive strength of caliche increases logarithmically with increasing carbonate content. Bulk density increases linearly with increasing calcium carbonate content. Infiltration rates decrease with increasing calcium carbonate content. Petrocalcic horizons and laminar layers have the highest compressive strengths and bulk densities and the lowest infiltration rates. These properties not only vary with the distribution of caliche type, but also vary with age of the soil and depth in the soil profile.

5) Calcium carbonate cementation of alluvial material reduces it erodibility and controls landscape develop. Alluvial basins which display well-developed cementation have multiple fan and terrace surfaces. Case-hardening cements the banks of streams, and gully-bed cementation cements their floors. These and other types of $CaCO_3$ cement reduce the width of channel and increase its depth, and lower channel sinuosity. Infiltration is minimal on caliches resulting in excessive runoff and flooding in regions adjacent caliche. Caliche does not affect the length of stream channels per area (drainage density) but reduce the number of stream channels per area (drainage frequency).

6) The following conditions are those most favorable for caliche development; areas having these conditions contain well-developed caliche and should be avoided when siting MX Systems:

(a) alluvial materials composed of carbonate clasts or clasts derived from basic igneous rocks;

(b) alluvial materials situated downwind a source for fine grained $CaCO_3$, such as playas, floodplains, etc.;

(c) alluvium adjacent to or overlying gypsiferous deposits;

(d) coarse, poorly sorted alluvium with low voids space;

(e) older alluvium or oder geomorphic surfaces;

(f) and stable geomorphic surfaces which are not subjected to accelerated erosion and deposition.

7) Caliches that are shallowly buried or exposed at the surface can be detected by density contrasts on satellite imagery. Caliche has high variances of image density. Additionally, caliche affects the morphology of the landscape and this may be useful for its detection. Commonly near-surface caliche areas have drainage densities less than 16 km/km$^2$. In addition caliche preserves fan surfaces in the shape of finger-like ridges which are light-toned.

## REFERENCES AND LITERATURE CITED


Adams, G. T., 1974, Laminar-layered calcium carbonate deposits on the Red Rock Canyon Alluvial fan, Clark County, Nevada: unpub. MS. Thesis, Univ. of Cincinnati, 86 pp.

Aristarain, L. F., 1962, Caliche deposits of New Mexico: unpub. Ph. D. Dissertation, Harvard Univ.

__________, 1970, Chemical analyses of caliche profiles from the High Plains, New Mexico: Jour. Geology, v. 78, p. 201-212.

__________, 1971, Clay minerals in caliche deposits of eastern New Mexico: Jour. Geology, v. 79, P. 75-90.

Arkley, R. J., 1963, Calculation of carbonate and water movement in soil from climatic data: Soil Sci. v. 96, p. 239-248.

Bagnold, R. A., 1941, The physics of blown sand and desert duens. Morrow, New York, 265 p.

Blake, W. P., 1902, The caliche of southern Arizona, An examination of deposition by vadose circulation: Trans. Amer. Inst. Min. Met Eng., v. 31, p. 220-226.

Blank, H. R. and E. W. Tynes, 1965, Formation of caliche in-situ: Geol. Soc. America Bull., v. 75, p. 1387-1391.

Breazeale, J. F. and H. v. Smith, 1930, Caliche in Arizona: Univ. Arizona Agri. Exp. Station Bull., v. 131, p. 419-441.

Bretz, J. H. and L. Horberg, 1949, Caliche in southeastern New Mexico: Jour. Geology, v. 57, p. 491-511.

Brewer, R., 1964, Fabric and Mineral Analysis of Soils: John Wiley and Sons, New York, 470 p.

__________, 1972, The basis of interpretation of soil micromorphological data: Geoderma, v. 8, p. 81-94.

Brown, C. N., 1956, The origin of caliche on the northeastern Llano Estacado, Texas: Jour. Geology, v. 64, p. 1-15.

Buckman, H. O. and B. C. Brady, 1969, The nature and properties of soils: The McMillan Co., Toronto, Canada 653 p.

Buol, S. W., 1965, Present soil-forming factors and processes in arid and semiarid regions: Soil Science, v. 99, p. 45-49.

Cailleux, A., 1965, Quaternary secondary chemical deposition in France: Geol. Soc. America Sp. Paper 84, p. 125-139.

Chamberlain, E. G. and M. L. Richardson, 1974, Report and Interpretations for the General Soil Map of Yuma Connty, Arizona, United States Dept. of Agriculture Soil Conservation Service.

Cooke, R.U. and Warren A., 1973, Geomorphology in Deserts, Univ of Calif. Press, Los Angeles, 374 pp.

Cooley, M. E., 1961, Description and origin of caliche in the Glen-San Juan canyon region, Utah and Arizona: Arizona Geol. Soc. Digest, v. 4, p. 35-41.

Cooley, R. L., G. W. Fiero, Jr., L. H. Lattman and A. L. Mindling, 1973, Influence of surfce and near-surface caliche distributionn on infiltration characteristics and looding, Las Vegas area, Nevada: Center for Water Resource Research, Desert Res. Inst. Proj. Rept. 21, 41 pp.

Crawford, R. E., Higgins, C. J., and Boltmann, E. H., 1974, The Air Force Manual for Design and Annalysis of Hardened Structures: AFWL -TR-74-102, 1118 pp.

Cuyler, R. H., 1930, Caliche as a fault indicator: Geol. Soc. America Bull., v. 41, p. 109 (abst).

Degens, E. T., 1965, Geochemistry of Sediments: Prentice-Hall, Englewood Cliffs, New Jersey, 342 pp.

Engel, C. G. and R. P. Sharp, 1958, Chemical data on desert varnish. Bull. Geol. Soc. Amer. 69: p. 487-518.

Flach, K. W., w. d. Nettleton, L. H. Gile, and J. G. Cady., 1969, Pedocementation: Indurationn by silica, carbonates and sesqui-oxides in the Quaternary. Soil Sci., v. 107, p. 442-453.

Folk, R. A., 1959, Practical petrographic classification of lime-stones: Amer. Assoc. Petroleum Geologists Bull., v. 43, p. 1-38.

Grye, J. C., H. D. Glass, A. B. Leonard and D. D. Coleman, 1974, Caliche development and clay mineral zonation of the Ogallala Formation in central-eastern New Mexico: New Mexico Bureau Mines and Minerlas Resources Circ. 144, 16 pp.

Gardner, L. R., 1968, The Quaternary geology of the Moapi Valley, Clark County, Nevada: unpub. Ph.D. dissertation, Penn. State University, University Park, Pa.

__________, 1972, Origin of the Mormon Mesa Caliche, Clark County, Nevada: Geol. Soc. America Bull., v. 83, p. 143-156.

Garrels, R. M. and C. L. Christ, 1965, Solutions, Minerals and Equilibria: Harper and Row, New York, p. 93-122.

Gile, L. H., 1961, A classification of Ca horizons in soils of a desert region, Dona Ana County, New Mexico: Soil Sci. Soc. America Proc. v. 25, p. 52-61.

__________, F. F. Peterson and R. B. Grossman, 1965a, The K horizon: a master soil horizon of carbonate accumulation: Soil Science, v. 99, p. 74-82.

__________, and J. W. Hawley, 1966, Periodic sedimentation and soil formation on an alluvial-fan piedmont in southern New Mexico: Soil Sci. Soc. America Proc., v. 30, p. 261-268.

__________, F. F. Peterson and R. B. Grossman, 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Sci. v. 101, O. 347-360.

Gile, L. H., 1966, Cambic and certain noncambic horizons in desert soils of southern New Mexico: Soil Sci. Soc. America Proc., v. 30, p. 773-781.

__________, 1967, Soils of ancient basin floor near Las Cruces, New Mexico: Soil Sci., v. 103, p. 264-276.

__________, and R. B. Grossman, 1968, Morphology of the argillic horizon in desert soils of southern New Mexico: Soil Sci., v. 106, p. 6-15.

Gile, L. H. and J. w. Hawley, 1968, Age and comparative development of desert soils at the gardner Spring Radiocarbon Site, New Mexico. Soil Sci. Soc. American Proc. 32, p. 709-716.

Gile, L. H., Hawley, J. W. and R. B. Grossman, 1970, Distribution and genesis of soils and geomorphic surfaces in a desert region of southern New Mexico: Guidebook, Soil Geomorphology Field Conf., Soil Science Soc. America, 156 p.

Gile, Leland H., 1970, Soils of the Rio Grande Valley border in southern New Mexico. Soil Sci. Soc. America Proc. 34, p. 465-472.

Gile, L. H., and J. W. Hawley, 1972, The predicition of soil occurrence in certain desert regions of the southwestern United states. Soil Sci. Soc. America Proc. 36, p. 119-124.

Gile, L. H., 1974, Causes of Soil Boundaries in an Arid Region: I. Age and Parent Materials. Soil Sci. Soc. America Proc., v. 39, p. 316-330.

Gile, L. H. 1975a, Causes of soil boundaries in an arid region: I. Age and parent materials. Soil Sci. Soc. America Proc. 39 p.316-323.

Gile, L. H., 1975b, causes of soil boundaries in an arid region: II. Dissection, moisture, and faunal activity. Soil Sci. Soc. America Proc. v. 39, p. 324-330.

Gile, L. H., 1975c, Holocene soils and soil-geomorphic relations in an arid region of southern New Mexico. Quaternary Research v. 5, p. 321-360.

Gile, L. H. and R. B. Grossman, 1979, The Desert Project Soil Monograph, United States Dept. of Agriculture, Soil Conservation Service.

Gillete, H. S., 1934, Soil tests useful in determinging quality of caliche: Public Roads, v. 15, p. 237-242.

Goss, D. W., S. J. Smith and B. A. Stewart, 1973, Movement of added clay through calcareous materials. Geoderma, 9, 97-103.

Goudie, A. S., 1971, A regional bibliography of calcrete: in Food, Giver and the Arid Lands, W. G. McGinnies, B. J. Goldman and P. Paylore eds., Univ. Arizona Press, Tucson, p. 421-437.

__________, 1972, The Chemistry of World calcrete deposits Jour. Geology, v. 80, p. 449-463.

__________, 1973, Duricrusts in Tropical and Subtropical Landscapes: Clarendon Press, Oxford, England, 174 pp.

Harrison, R. S., 1973, Caliche profiles of Barbados (west Indies): Processes, Products, and controlling parameters: Geol. Soc. America abstracts, p. 653.

Hartman, G. W., 1973, General Soil Map, Maricopa County, Arizona, United States Dept. of Agriculture, Soil Conservaton Service.

Hawker, H. W., 1927, A study of the soils of Hidalgo County, Texas, and the stages of their soil-lime accumulaiton: Soil Sci., v. 23, p. 475-485.

Hawley, J. W. and L. H. Gile, 1966, Landscape evolution and soil genesis in the Rio Grande region, southern New Mexico: in 11th/Ann. Field Conf. Guidebook, Rocky Mt. Sections, Friends of the Pleistocene, 74 pp.

Hawley, J. W., 1965, Geomorphic surfaces along the Rio Grande Valley from El Paso, Texas, to Caballo Reservoir, New Mexico: New Mexico Geol. Soc. Guidebook of Southwestern New Meixco, II, p. 188-198.

Hawley, J. W. 1975, The Desert Soil-Geomorphology Project. In Guidebook of the Las Cruces Country: New Mexico Geol. Soc. Guidebook 26.

Hooke, R. L., H. Y. Yange and P. W. Weiblen, 1969, Desert varnish: an electron probe study: Jour. Geology 77, p. 275-288.

Hunt, C. B., 1978, Surficial Geology of Southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 42.

Hunt, C. B., 1978, Surficial Geology of Southeast New Mexico: New Mexico Bureau of Mines and Mineral Resources. Geologic map 41.

James, N. P., 1972, Holocene and Pleistocene calcareous crust (caliche) profiles: criteria for subaerial exposure: Jour. Sed. Petrology, v. 42, p. 817-836.

Jennings, J. N. and M. Sweeting, 1961, caliche pseudoanticlines in the Fitzroy Basin, Western Australia: Am. Jour. Science, v. 259, p. 635-639.

Jenny, H., 1941, Factors of Soil Formation: McGraw-Hill Book Co., New York.

Junge, C. E. and R. T. Werby, 1958, The concentration of chloride, sodium, potassium, calcium, and sulfate in rain water over the United States: Jour. Meteorology, v. 15, p. 417-425.

Kaplan, A. E., 1973, The Geomorphology of McCullough Alluvial Fan, Clark County, Nevada: Unpubl. MS Thesis, Univ. of Cincinnati, 69 pp.

Krauskopf, H. A., 1967, Introduction to Geochemistry: McGraw Hill, New York, 721 p.

Ku, T. L., W. B. Bull, S. T. Freeman and K. G. Knauss, 1979, $Th^{230}$ - $U^{234}$ dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, Southeastern California: Geol. Soc. America Bull., v. 90, p. 1063-1073.

Lamplugh, G. W., 1902, Calcrete: Geol. Magazine, v. 9, p. 575.

Lattman, L. H., 1971, Geomorpholgoy of the East Flank of the Spring Mts., Nevada: Air Force Cambridge Research Laboratories, Rept. ADCRL-71-0326, 89 pp.

Lattman, L. H. and E. M. Simenberg, 1971, Case-hardening of carbonate alluvium and colluvium Spring Mountains, Nevada: Jour. Sed. Petrology, v. 41, p. 274-281.

Lattman, L. H., 1973, Calcium carbonate cementation of alluvial fans, in southern Nevada: Geol. Soc. America Bull., v. 84, p. 3013-3028.

Lattman, L. and S. K. Lauffenburger, 1974, Proposed role of gypsum in the formation of caliche: Zeit. Geomorph. v. 20, p. 140-149.

Lattman, L. H., 1975, Factors Affecting Development and Opitonal Photomapping Technique of Calcium Carbonate Cementation of Arid Region Sediment. US Army Research Office, Rept. DA-ARO-D-31—124-71-6-137, 25 pp.

Lee, W. T., 1905, Underground waters of the Salt River Valley, Arizona: U. S. Geol. Survey Water Supply Paper 136, 196 pp.

Lenhart, R., 1974, An Evaluation of ERTS Imagery for Remote Sensing of Alluvial Fans in Nevada: Unpubl. MS Thesis, Univ. of Cincinnati, 69 pp.

Lonsdale, J. T., 1926, The occurrence of caliche in Oklahoma: Okla. Univ. Bull. 330, p. 132-136.

Maker, H. J., D. N. Cox, and J. V. Anderson, 1970, soil Associatipms and Land Classification for Irrigation, Hidalgo County: New Mexico State University Agrigultural Experiment Station Research Report 177.

Maker H. J., R. E. Neher, P. H. Derr, and J. V. Anderson, 1971, ns and Land Classification for Irrigation Dona Ana County: New Mexico State University Agricultural Experiment Station Research Report 183.

Maker, H. J., R. E. Heher and J. V. Anderson, 1971, Soil Associations and land Classification for Irrigation Grant County: New Mexico State University Agricultural Experiment Station Research Report 200.

Mason, R. J., A. B. A. Brind and K. Knight, 1950, Pleistocene Climatic significance of calcretes and ferricretes; Nature, v. 184, p. 568.

Matthews, R. K., 1968, Carbonate diagenesis: equilibrium of sedimentary mineralogy to the subaerial environment: coral cap of Barbados, West Indies: Jour. Sed. Petrology, v. 38, p. 1110--1119.

Miller J. P., 1952, A portion of the system calcium carbonate-carbon dioxide water, with geological implications: America Jour. Sci., v. 250, p. 161-203.

Mountain, M. J., 1967b, The location of pedogennic materials using aerial photographs, with some examples from South Africa: In Proc. 4th/Reg. Conf. Africa Soil Mech. Fund. Eng., v. 1, p. 35-40.

Nettleton, W. D., J. E. Witty, R. E. Nelson, and J. W. Hawley. 1975, Genesis of argillic horizons in soils of desert areas of the Southwestern United States. Soil Sci. Soc. America Proc. v. 39, p. 919-926.

Netterberg, F., 1969, Ages of calcretes in Southern Africa: South African Arch. Bull, v. 24, p. 88-92.

__________, 1971, Calcrete in road construction: Natl. Inst. Road Research Bull., v. 10, 73 pp.

Netterberg, F., 1966, Calcrete research project progress report RS/8/7: Counc. Sci. and Indust. Resch., Natl. Inst. Road Resch., Pretoria.

__________, 1967, Some roadmaking properties of South African calcretes: Proc. 4th Reg. Conf. Soil Mechanics and Foundation Engineering, Cape Town, S. Africa, p. 77-81.

__________, 1969a, The geology and engineering properties of South African calcretes: unpub. Ph.D. dissertation, Univ. Witwatersrand, Johannesburg, South Africa.

__________, 1969b, The interpretation of some basic calcrete types: South African Arch. Bull., v. 24, p. 117-122.

Olson, S. R. and F. S. Watanbe, 1959, Solubility of calcium carbonate in calcareous soils: Soil Sci., v. 88, p. 123-129.

Price, W. A., 1925, Caliche and pseudoanticlines: Amer. Assoc. Petroleum Geologists Bull., v. 9, p. 1009-1017.

__________, 1933, Reynosa problem of south Texas, and origin of caliche: Am. Assoc. Petroleum Geologists Bull., v. 17, p. 488-522.

__________, 1940, Caliche karst: (abst) Geol. Soc. America Bull., v. 51, p. 1938.

__________, M. K. Elias and J. C. Frye, 1946, Algae reefs in caprock of Ogallala Fomration, Llano Estacado plateau, New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 30, p. 1742-1746.

Purcell, C. W., Jr., 1973, Eolian Transport: A Process Supplying Carbonate Material for Caliche Formation: Unpubl. MS Thesis, Univ. of Cincinnati, 6 pp.

Richardson, M. L. and M. L. Miller, 1974, Report and Interpretations for the General Soil Map, Pina County, Arizona United States Dept. of Agriculture Soil Conservation Service.

Richmond, D. L. and M. L. Richardson, 1974, General Soil Map and Interpretations, Mohave County, Arizona United States Dept. of Agriculture Soil Conservation Service.

Reeves, C. C., Jr., and J. D. Suggs, 1964, Caliche of central and southern Llano Estacado, Texas: Jour. Sed. Petrology, v. 34, p. 669-672.

Reeves, C. C. Jr., 1970a, Origin, classification and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico: Jour. Geology v. 78, p. 353-362.

Reeves, C. C. Jr., 1971, Relations of caliche to small natural depressions, southern High Plains, Texas and New Mexico: Geol. Soc. America Bull., v. 82, p. 1983-1988.

Reeves, C. C., Jr., 1976, Caliche: Estacado Books, Lubbock, Texas, 233pp.

Roques, H., 1969, A review of present-day problems in the physical chemistry of carbonates in solution: Trans. C.R.G., v. 11, p. 139-163.

Ruhe, R. V., 1965, Quaternary paleopedology: <u>in</u> The Quaternary of *the United States*, H. E. *Wright and* D. G. Frey, editors: Princeton Univ. Press, Princeton, New Jersey, p. 755-764.

Sharma G. D., 1965, Formation of silica cement and its replacement by carbonates: Jour. Sed. Petrology, v. 35, p. 733-745.

Shinn, E. A., 1968, Practical significance of Birdseye structures in carbonate rocks: Jour. Sed. Petrology, v. 38, p. 215-223.

Shreve, F. and T. D. Mallery, 1933, The relation of caliche to desert plants: Soil Sci., v. 35, p. 99-113.

Sidwell, R., 1943, Caliche deposits on the southern High Plains, Texas: Am. Jour. Sci., v. 241, p. 257-261.

Smith, H. T. U., 1940, Geologic studies inn southwestern Kansas: Kansas Geol. Surv. Bull. 34.

Smith, R. M., P. C. Twiss, R. K. Krauss and M. J. Borwn, 1970, Dust deposition in relation to site, season and climactic variables: Soil Sci. Soc. America Proc., v. 34, p. 112-117.

Sofoulis, F. 1963, The occurrence and hydrological significance of calcrete deposits in Western Australia: Annual Rept. (1962) Geol. Sur. Western Australia, p. 38-42.

Soil Survey Staff, 1960, Soil classification, A comprehensive system, 7th/approximation: U. S. Govt. Printing Office.

Strakhov, N. H., 1970, Principles of Lithogenesis, vol. 3: Plenum Pub. Co., New York, 577 pp.

Stuart, D. M., M. A. Fosberg and G. C. Lewis, 1961, Caliche in southwestern Idaho: Soil Sci. Soc. Proceedings, Div. p. 132-135.

Uppal, H. L. And R. L. Nanda, 1968, Survey of hidden calcrete in alluvial plains of India by airphoto interpretation: Proc. 4th/Conf. Australian Road Resch. Board, v. p. 1677-1687.

Van Arsdale, R., 1974, The Influence of Caliche on the geometry of Arroyos near Buckeye, Arizona: Unpubl. MS Thesis, Univ. of Cincinnati, 69 pp.

Vanden Heuvel, R. C., 1966, The occurrence of sepiolite and attapulgite in the calcareous zone of a soil near Las Cruces, New Mexico: in Nat. Conf. Clays and Clay Minerals, 13th, 1694, Proc., Oxford, Permagon Press, p. 193-207.

Vogt, K. D. and M. L. Richardson, 1974, Report and Interpretations for the general Soil Map of Gila County Arizona, United States Dept. of Agriculture Soil Conservation Serice.

Von Der Borch, C. C., 1965, The distribution and preliminary geochemistry of modern carbonate sediments of the Coorong area, south Australia: Geochim. Cosmo. Acta, v. 29, p. 781-799.

Walker, T. R., 1960, Carbonate replacement of detrital cyrstalline silicate minerals as a source of authigenic silica in sedimentary rocks: Geol. Soc. America Bull., v. 71, p. 145-152.

Weider, M. and D. H. Yaalon, 1974, Effect of matric composition on carbonate nodule crystallization: Geodermia, v. 11, p. 95-121.

Wells, S. G., 1976, A study of surficial Processes and Geomorphic History of a basin the Sonoran Desert, Southwestern Arizona; Unpubl. Ph.D. Dissertation; Univ. of Cincinnati, 328 pp.

__________, 1977, Nature and prediction of calcium carbonate cementation (caliche) in alluvial basins of southwestern U. S.: 1977 USAD-ASEE Summer Faculty Research Program Research Reports, v. 2, Rept. «43 (AFSOR-TR-78-0349), 42 pp.

Williams, G. E. and H. A. Polach, 1969, The evaluation of $^{14}C$ ages for soil carbonate from the arid zone: Earth and Planetary Sce. Letters, v. 7, p. 240-242.

Williams, G. E. and H. A. Polach, 1971, Radiocarbon dating of arid--zone calcareous paleosols: Geol. Soc. America Bull., v. 82, p. 3069-3086.

Winchester, P. D., 1972, Caliche-like limestones in the Lower Permain Laborcita Formation of the Sacramento Mountains, New Mexico: Geol. Soc. America (abst), v. 4, p. 707.

Yaalon, D. H., 1971, Soil-forming processes in time and space: in Paleopedology-Origin, Nature and Dating of Paleosols, D. H. Yaalon ed.,; Int. Soc. Soil Sci. and Israel Univ. Press, p. 29-39.

Yaalon, D. H. and E. Ganor. 1973. The influence of dust on soils during the Quaternary, Soil Sci. IV 16, p. 146-155.

Yaalon, D. H., 1954b, Calcareous soils of Israel: Israel Exp. Journal, v. 4, p. 278-285.

Appendix A

General Locations of Selceted Field Stations

Study Area A:

Station 1 - terrace along Salt River, on Higley Road, northeast of Mesa, Arizona.

Station 2 - dissected pediment along Bush Highway, east of Mesa, Arizona.

Station 3 - terrace along Verde River near the Beeline Highway north of Scottsdale, Arizona.

Station 4 - alluvial fan surface on the southeastern flank of the Harquahala Mountains, south of Aquila, Arizona.

Station 5 - exposure in bottom of Tiger wash in Harquahala Valley, southeast of Salome, Arizona.

Study Area B:

Station 6 - alluvial fan surface on Silver Creek wash, southeast of Bullhead City, Arizona.

Station 7 - alluvial fan surface along the Topock-Oatman Road and along the western flank of the Black Mountains, south of Oatman, Arizona.

Station 8 - exposure at fan-bedrock contact along the Topock—Oatman Road, south of Oatman, Arizona.

Study Area C:

Station 9 - alluvial fan surface of McCullogh fan, approximately 1.5 km east of Highway 41 and east of Las Vegas, Nevada.

Station 10 - alluvial fan surface of McCullough fan, east of Las Vegas, Nevada.

Station 11 - fan and terrace surfaces of Red Rock Canyon, west of Las Vegas, Nevada.

Station 12 - exposure in alluvial fan of Red Rock Canyon, west of Las Vegas, Nevada.

Only those field stations referred to in specific sample descriptions have been included in this report. Other stations were taken in Study Area D and in selected areas of southern New Mexico.

# Appendix B

## Refluxing Laboratory Experiment to Measure Amounts and Rates of Parent Material Weathering

Topic: Laboratory experiment conducted on known granite and basalt samples to simulate weathering over an extended period.

Purpose: To determine how much calcium and magnesium ions are released into solution and made available for formation of pedogenic caliche.

Knowns: 1) Location, composition and age of granite and basalt samples. (Table B1).

2) Volume or weight of each rock used.

3) Quality and quantity of water used.

Lab set-up: The rock samples were broken into a specific phi size which allow the samples to fit into a 250 milliliter round bottom flask. The volume and sizes of the two rock types were equal. The flask was filled with a known quantity of distilled water and then attached to a refluxing apparatus (Figure B-1). This unit was then placed on a hot plate and heated continuously at boiling temperature (equal or approximately 95°C) for an extended period. Periodic water samples were taken and analysized by atomic absorption for all important ions and their concentrations.

Experiment:

The experiment was designed so that small cubes of a basalt and granite were refluxed in boiling deionized water for 72 days to determine the amount of calcium and magnesium leached from each rock type. This method was used to simulate weathering in the field but at a much faster rate. The purpose of this weathering experiment was to check the hypothesis that a large percentage of the calcium in caliche is from direct in-situ weathering of the low-carbonate parent rock.

The lab set-up consisted of one hotplate with three reflux condensers inserted into three 250 milliliter flat-bottom flasks (Figure B-1). Four cubes of each rock type (Table B-2) were cleaned with distilled water, dried with acetone and placed into two of the acid-washed (6N HCl) 250 ml flat-bottom flasks. 150 ml deionized water was added to these flasks by pipet. Acid washed (6N HCl) reflux condensers were attached and placed on the hotplate to boil gently for the 72 day period. A third reflux assembly was set up identically to the other two but containing several acid washed glass beads and was used as a control in the leaching experiment.

The samples and control were refluxed, and five ml aliquots were extracted periodically over the 72 day experiment. Initially the calcium and magnesium were analyzed by atomic absorption by direct atomization of the extracted aliquot into an air-acetylene flame. The air-acetylene flame was chosen because of noise and sensitivity characteristics. As the experiment progressed however, it became evident that other ions, chiefly Na and Si began to cause chemical interference in the flame. Therefore, on the 29th day of the experiment, conversion was made to a hotter nitrous oxide-acetylene ($N_2O-C_2H_2$) flame to eliminate chemical interferences. In order to minimize ionization interferences in the $N_2O-C_2H_2$ flame, the samples, standards and control were made up to contain 1000 μg/ml Cesium in 10% hydrochloric acid (HCl). After the final run on the day 72, the remaining solution was analyzed for the following elements: Fe, Na, K and Si. These results are given in Table B-3. Plots of magnesium and calcium concentration versus time are given in Figures B-2 and B-3 respectively. These graphs are derived only from samples taken after the 29 day of the experiment and analyzed in the $N_2O-C_2H_2$ flame. Least squares regressions were determined for the basalt and granite data on both the magnesium and calcium graphs. These plots do no intersect the origin because of probable contamination of the sample due to cutting. Figures B-2 and B-3 show that neither calcium or magnesium were being leached out in any measurable quantities from the granite sample. The graphs do show a definite leaching of both calcium and magnesium from the basalt sample. These trends and amount of leaching per day during the experiment are summarized in Table B-4.

Table B-1. Whole rock analysis of clasts used in reflux experiment.

| | Basalt | Granite |
|---|---|---|
| $SiO_2$ | 47.87 | 77.51 |
| $Al_2O_3$ | 14.91 | 13.00 |
| $Fe_2O_3$ | 5.07 | 0.44 |
| FeO | 8.86 | 0.13 |
| MgO | 5.74 | 0.15 |
| CaO | 7.17 | 0.26 |
| $Na_2O$ | 2.91 | 3.40 |
| $K_2O$ | 1.97 | 4.82 |
| $H_2O(+)$ | 1.81 | 0.40 |
| $CO_2$ | 0.45 | |
| $H_2O(-)$ | 0.05 | 0.00 |
| $TiO_2$ | 2.21 | 0.10 |
| $P_2O_5$ | 0.31 | 0.01 |
| Sulfur | 0.26 | ----- |
| MnO | 0.194 | 0.035 |
| SrO | 0.034 | 0.001 |
| Total | 99.82 | 100.25 |

Table B-2. Sample dimensions and weights used in experiment.

<u>Samples</u>: Four cubes of each rock type were used in the experiment. The listing below the weight and total surface area of the cubes for each rock type.

| Granite | Basalt |
|---|---|
| 6.2869 gr | 6.5195 gr |
| 6.6042 gr | 7.7376 gr |
| 6.4572 gr | 7.5508 gr |
| 5.9134 gr | 7.6646 gr |
| 25.2617 grams | 29.4725 grams |

| Granite total surface area | Basalt total surface area |
|---|---|
| $44.64\ cm^2$ | $43.86\ cm^2$ |

Table B-3 Chemical analysis of final solution.

| | μg/ml in final solution | | | μg/ml in rinse solution (20 ml 1:1 HCl + cesium diluted to 100 ml). | | |
|---|---|---|---|---|---|---|
| Element | Blank (control) | Basalt | Granite | Control | Basalt | Granite |
| Fe | <1.5 | <1.5 | <1.5 | <0.75 | <0.75 | <0.75 |
| Na | 4.8 | 10.8 | 0.65 | <0.15 | <0.15 | <0.15 |
| K | <0.20 | 3.0 | 2.2 | <0.10 | <0.10 | 0.20 |
| Si | 72.0 | 170.0 | 18.0 | <2.0 | <2.0 | <2.0 |
| Mg | 0.0 | 6.5 | 2.3 | | | |
| Ca | -0.1 | 9.4 | 3.7 | | | |

Table B-4. Amount of Calcium and Magnesium Leached

| | Basalt | Granite | Basalt | Granite |
|---|---|---|---|---|
| Calcium | 0.0357 $\frac{\mu g/cm^2}{day}$ | No apparent leaching | .1285 $\frac{grams/meter^2}{year}$ | No apparent leaching |
| Magnesium | 0.0179 $\frac{\mu g/cm^2}{day}$ | No apparent leaching | .0644 $\frac{grams/meter^2}{year}$ | No apparent leaching |

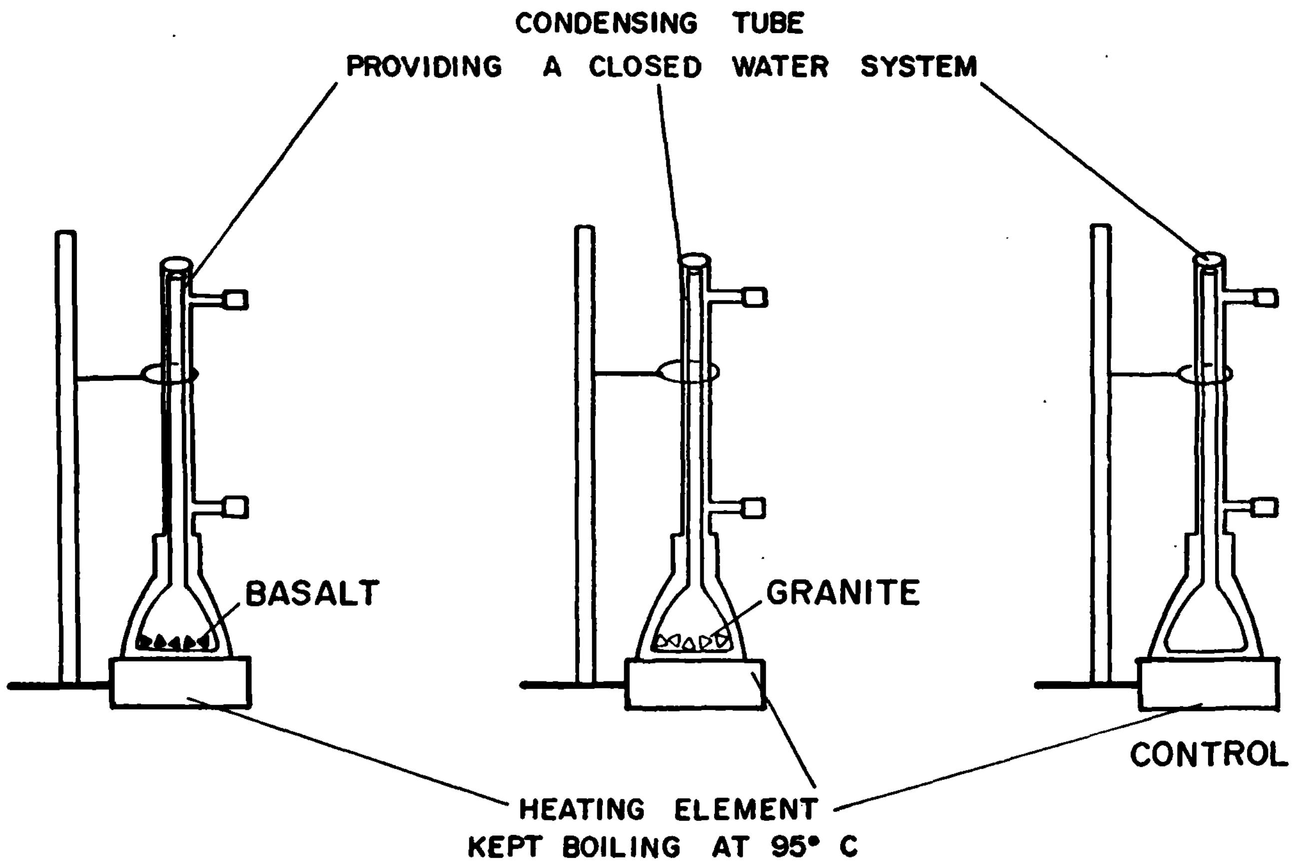



Figure B-1. Refluxing apparatus and set-up for calcium and magnesium weathering experiment.

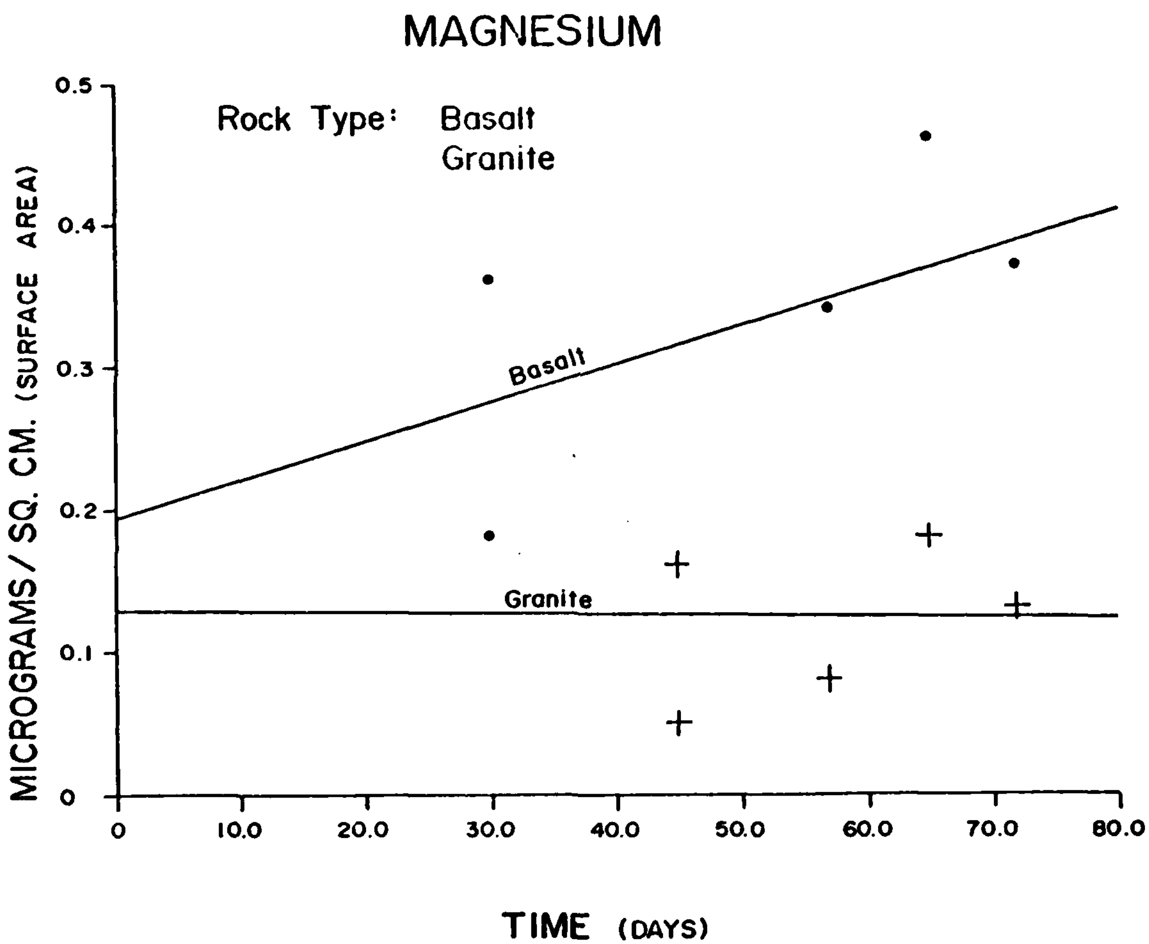



Figure B-2. Weathering rate of magnesium from granite and basalt samples determined in the laboratory.

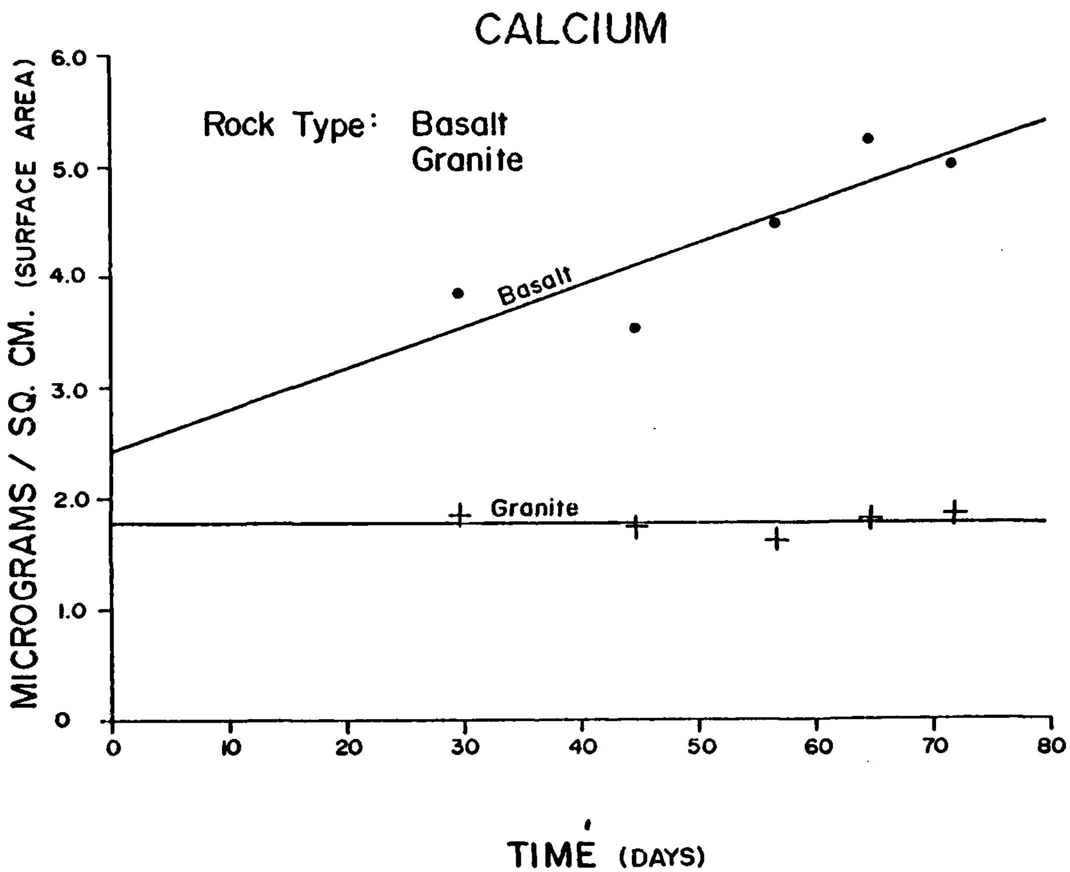



Figure B-3. Weathering rate of calcium from granite and basalt samples determined in the laboratory.

## Appendix C

Chemical Analysis of Selected
Pedogenic Caliche Samples
(Whole Rock Analysis by John Husler, Staff Chemist)

| Constituent | Sample Station (See Appendix A for location) | | | | |
|---|---|---|---|---|---|
| | S1-b | S1-c | S-2 | S-7 | S-11 |
| $SiO_2$ | 8.92 | 17.10 | 25.72 | 5.72 | 13.09 |
| $Al_2O_3$ | 1.22 | 1.89 | 3.02 | 1.08 | 1.08 |
| $Fe_2O_3$ | 0.33 | 0.54 | 0.65 | 0.17 | 0.14 |
| FeO | 0.17 | 0.15 | 0.24 | 0.14 | 0.12 |
| MgO | 1.04 | 1.17 | 1.74 | 0.89 | 1.35 |
| CaO | 46.99 | 42.20 | 35.00 | 49.90 | 45.10 |
| $Na_2O$ | 0.10 | 0.23 | 0.56 | 0.05 | 0.03 |
| $K_2O$ | 0.25 | 0.39 | 0.67 | 0.24 | 0.24 |
| $H_2O+$ | 4.20 | 2.97 | 3.18 | 4.14 | 2.38 |
| $H_2O-$ | 0.66 | 0.42 | 0.81 | 0.34 | 0.32 |
| $TiO_2$ | 0.09 | 0.14 | 0.21 | 0.06 | 0.05 |
| $P_2O_5$ | 0.148 | 0.045 | 0.173 | 0.067 | 0.032 |
| MnO | 0.007 | 0.011 | 0.014 | 0.006 | 0.004 |
| SrO | 0.043 | 0.034 | 0.028 | 0.046 | 0.022 |
| S | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| $CO_2$ | 35.35 | 32.45 | 27.38 | 36.83 | 35.58 |
| TOTAL | 99.52 | 99.74 | 99.40 | 99.68 | 99.54 |
| Total Fe (as $Fe_2O_3$) | 0.52 | 0.71 | 0.92 | 0.33 | 0.27 |
| L.O.I. | 39.54 | 35.41 | 30.53 | 40.96 | 37.95 |
| FeO after L.O.I. | 0.04 | 0.06 | 0.00 | 0.06 | 0.03 |

# Appendix D

*Petrographic Analysis of Selected Pedogenic Caliche Samples (see Appendix A for Sample locations)*

Sample S2-a:

Matrix: calcium carbonate

Mineral fragments:

| | | |
|---|---|---|
| 1. | Quartz | 78% |
| 2. | Microcline | 4% |
| 3. | Muscovite | 1% |
| 4. | Altered Plag | 5% |
| 5. | Biotite | 4% |
| 6. | Epidote (euhedral) | 2% |
| 7. | Perthite | 3% |
| 8. | Hornblende | 1% |
| 9. | Opaques | 2% |

Lower 3/4 of the slide is a petrocalcic horizon containing angular to subangular mineral fragments. Largest fragments are perthite and quartz; much of the feldspar is subangular and in beginning stages of weathering. Fragments range in size from 4 mm to a fine-grained groundmass << 1 mm. The most striking feature in low power is the color difference between the two layers; the lower petrocalcic layer containing the abundant fragments is light to dark gray in polarized light while the upper laminar layer is a dark brown with small (<< 1 mm) pellets a lighter brown. The pellets are usually aligned in subplanar manor. Most pellets have no inclusions - a few do contain angular quartz fragments which the pellets appear to have grown around. The mineral fragments are much less varied than in in the petrocalcic horizon; the laminar layer contains quartz and opaques with very little biotite, hornblende and epidote.

Sample S3-d2:

Matrix: calcium carbonate

| | | | |
|---|---|---|---|
| Mineral fragments: | 1. | Quartz (some sutured) | 60% |
| | 2. | Microcline (some perthitic) | 23% |
| | 3. | Biotite (some chlorite) | 1% |
| | 4. | Angite | <1% |
| | 5. | Opaques | 1% |
| | 6. | Altered feldspar<br>Euhedral calcite filling<br>secondary cracks and surrounding most<br>mineral fragments. | 15% |

Rock fragments: Quartz

Altered feldspar

Chlorite

The caliche contains two sizes of fragments: the larger (approx. 2-4 mm) are mostly quartz and microcline fragments which have secondary cracks that have been filled with calcite, the smaller (<< .5 mm) are subangular quartz, biotite, augite. The matrix is a bronze color in plane light (much different from most slides) and contains pellets of the matrix which are well rounded and are surrounded by euhedral calcite. These pellets do not differ in color or included mineral fragment (either size or comp). Grains up to 5 mm in diameter occur in this calcrete. All of these large grains are surrounded and filled by a secondary crystalline calcite.

Sample S7-S:

Matrix: calicum carbonate

Mineral Fragments:

| | | |
|---|---|---|
| 1. | Quartz | 94% |
| 2. | Opaques | 3% |
| 3. | Biotite | 3% |
| 4. | Hornblende | <<1% |

Density differences make macroscopic identification of four different layers possible with two of these being cryptocrystalline calcite and the other two containing some euhedral calcite. All mineral fragments are much less than 0.5 mm in size. Laminar layers are unusual because they contain many dissolution features which locally removed the lower layer before depositing a layer above and filling these pits. Upper laminar layer is displaced by a rock fragment.

Sample S9-d2:

Matrix: calcium carbonate

Mineral fragments: 5% Basaltic hornblende

2% Biotite

1% Augite

3% Opaques

Rock fragments: Basaltic Fragments 70%

Rock fragments are common. All are basic volcanic fragments which are well rounded. The caliche is a dense petrocalcic layer containing 25-30% volcanic fragments. The matrix is a dense calcium carbonate with euhedral calcite filling voids. Rock fragments range in size from 1 mm to approx. 6 mm. The minerals in the groundmass are small (<< .5 mm); dominantly quartz with some hornblende with biotite alteration rims and some opaques. The minerals in the groundmass are dominantly subangular. The textural maturity of the sediments in the calcrete is low as shown by the amount of hornblende, oxyhornblende, biotite,, augite and unaltered plagioclase present as well as the angularity of the mineral fragments in the groundmass. However, the rock fragments tend to be very well rounded.

Sample S7-11:

Matrix: calcium carbonate

| | | | |
|---|---|---|---|
| Mineral Fragments: | 1. | Quartz | 90% |
| | 2. | Epidote | 1% |
| | 3. | Hornblende | 1% |
| | 4. | Opaques | 5% |
| | 5. | Biotite | 3% |

These pelletoidal forms are grouped together into sub-horizontal layers. Secondary crack is filled with coarsely crystalline calcite and excludes all other mineral species found in the slide. The calcite which fills the crack has penetrated the porous walls of the crack forming an "aureole" of altered wall material up to 1.5 mm deep in the parent rock. Most mineral fragments are sub rounded but range from sub angular to rounded. The opaques are predominantly found in the later void and fracture fillings.

Sample S7-pc:

Matrix: Calcium Carbonate

Mineral Fragments:

| | | |
|---|---|---|
| 1. | Quartz (some sutured) | 56% |
| 2. | Biotite | 2% |
| 3. | Opaques | 1% |
| 4. | Hornblende | < 1% |
| 5. | Muscovite | < 1% |

Rock fragments: Basalt Fragments 40%

Series of greater and lesser densities of calcium carbonate; the lower layer is somewhat more dense than the middle layer and less dense than the upper layer. The lower layer is slightly laminated and contains small (<< 1 mm) grains of quartz, epidote, and opaques. The middle layer is separated from the lower by a dense gray to brown laminar layer 0.5 mm thick and containing very few inclusions. The middle layer contains more void space, a greater variety of mineral grains, and little or no lamination. Average grain size in this layer is approx. 0.25 mm. This layer has a color similar to the lower layer of light to dark gray while the upper laminar layer is a dense dark brown. The upper laminar layer varies in shades of brown between laminations with a few pellet-like forms in less dense layers. Quartz is the dominant mineral fragment of the upper layer. The textural maturity of S7-pc is very low with angular to sub-angular mineral fragments throughout. The presence of unstable (hornblende) species and the poor degree of sorting also indicate that the texutal maturity is low.

Sample S11-a1:

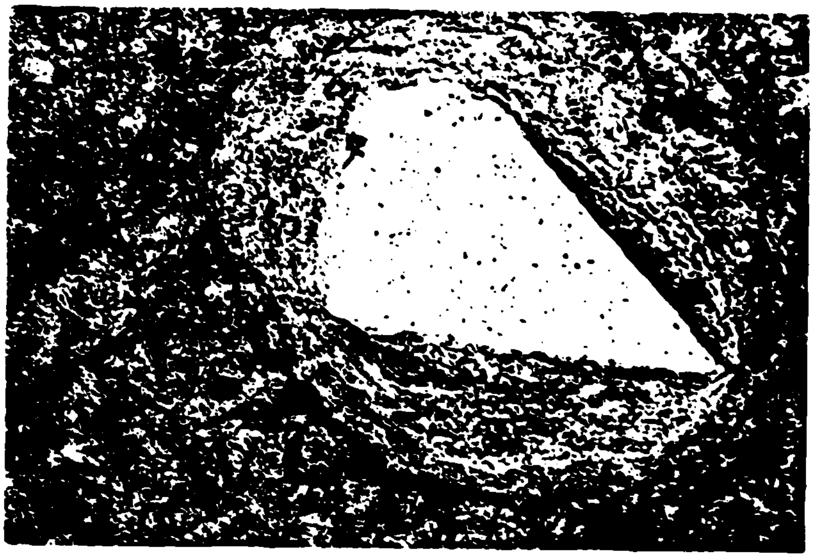
Matrix: cryptocrystalline calcium carbonate

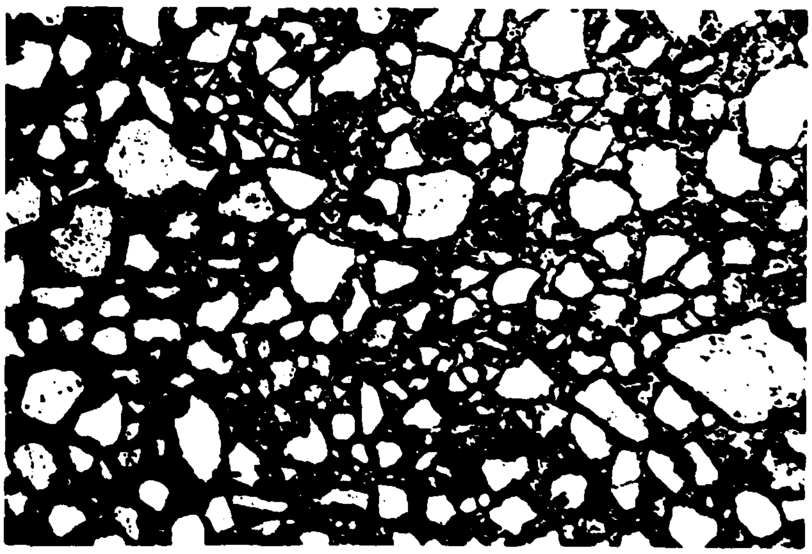
| | | | |
|---|---|---|---|
| Mineral Fragments: | 1. | Quartz | 60% |
| | 2. | Calcite | 39% |
| | 3. | Opaques | 1% |

Two observations distinguish this caliche from the rest: the lack of numerous different mineral species and the great abundance of mineral fragments relative to matrix. Mineral fragments range from sub-angular to sub-rounded with the greatest portion being more mature (sub-rounded). Two sized are dominant; the small (<< 1 mm) being quartz and the large (2-4 mm) being euhedral calcite (limestone) fragments. These larger fragments are sub-rounded to rounded.

Slide 52-a: Photo #6 — Very angular quartz grain within carbonate pisolite (16 power, 250 total magnification).

Slide 52-a: Photo #6a — Small rock fragments, approximately 70% quartz and 30% carbonates; note dense rind around fragments and all grains are suspended in matrix (2.5 power, 39 total magnification).





Slide 53-d2: Photo #7

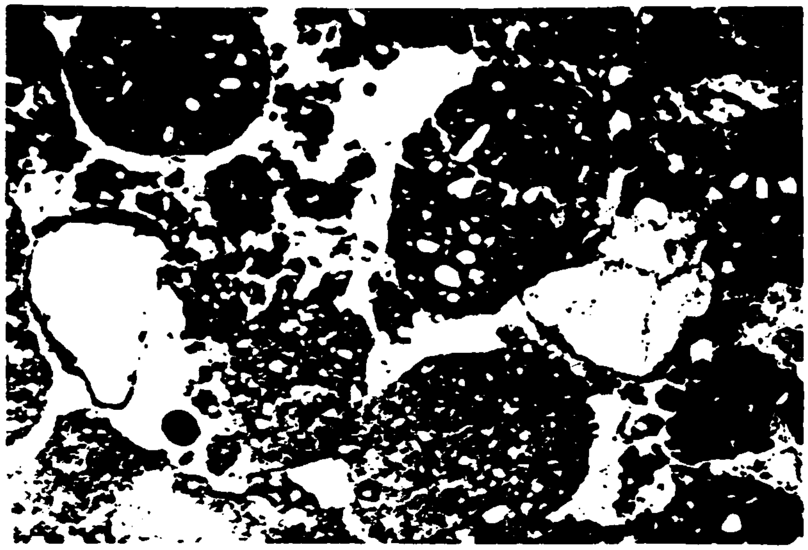
Pelletoids (cryptocrystalline) with small inclusions of angular quartz; pelletoids surrounded by microcrystalline subhedral calcite (plane light, 2.5 power, 39 total magnification.

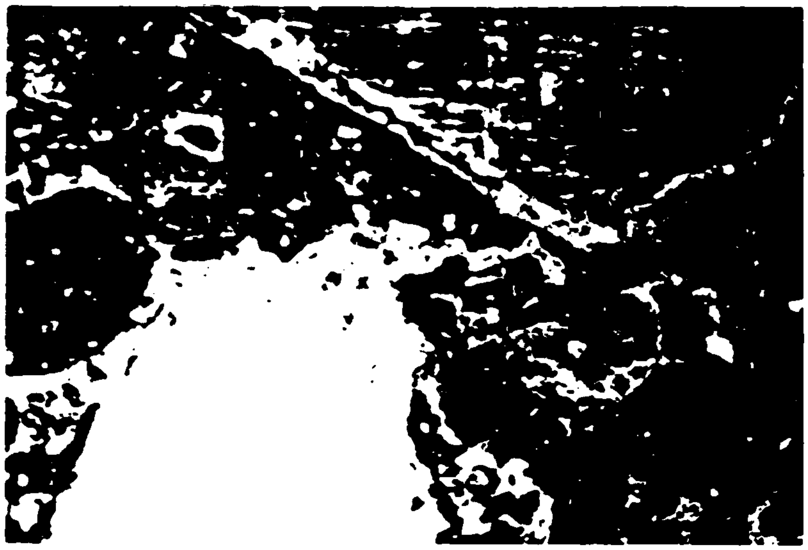
Slide 53-d2: Photo #8

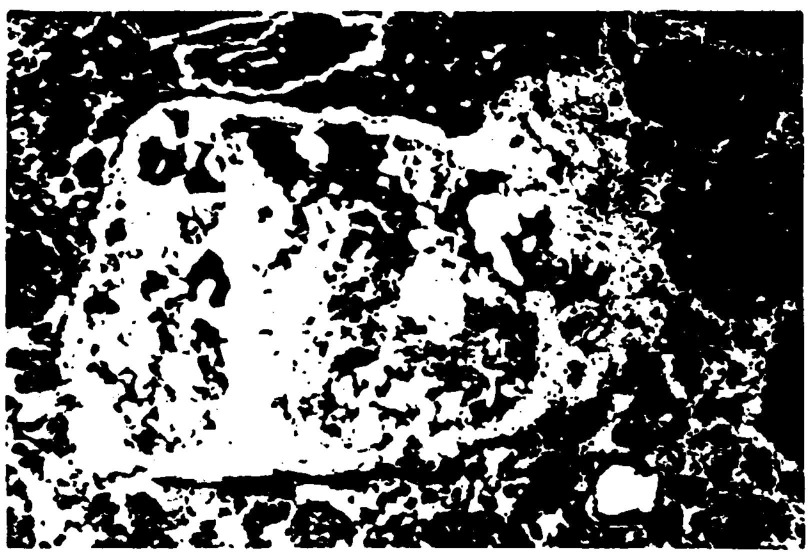
Microcline, quartz and pelletoids; all inclusions surrounded by microcrystalline calcite with some voids (X-nicols, 2.5 power, 39 total magnification).

Slide 53-d2: Photo #9

Polycrystalline or sutured quartz grain surrounded by microcrystalline calcite in pelletoid form (X-nicols, 2.5 power, 39 total magnification).



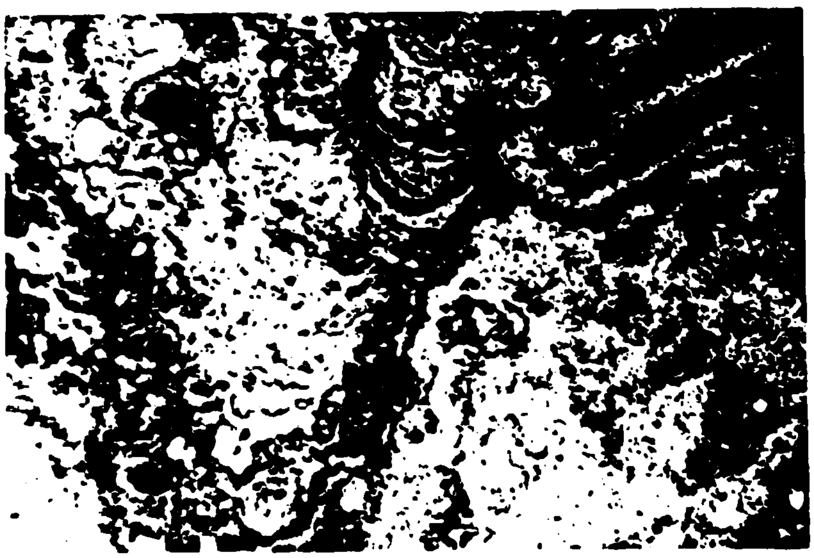




Slide 57-s: Photo #12 — Density differences in laminar layers with darker, crypto-crystalline calcite and lighter microcrystalline calcite (plane light, 2.5 power, 39 total magnification).

Slide 57-s: Photo #13 — Contorted, crypto-and microcrystalline calcite in laminar layer (plane light, 2.5 power, 39 total magnification).

Slide 57-s: Photo #14 — Tonal change due to cryptocrystalline and microcrystalline calcite in laminar layers; pendant structures filling voids formed by cracks (plane light, 2.5 power, 39 total magnification).

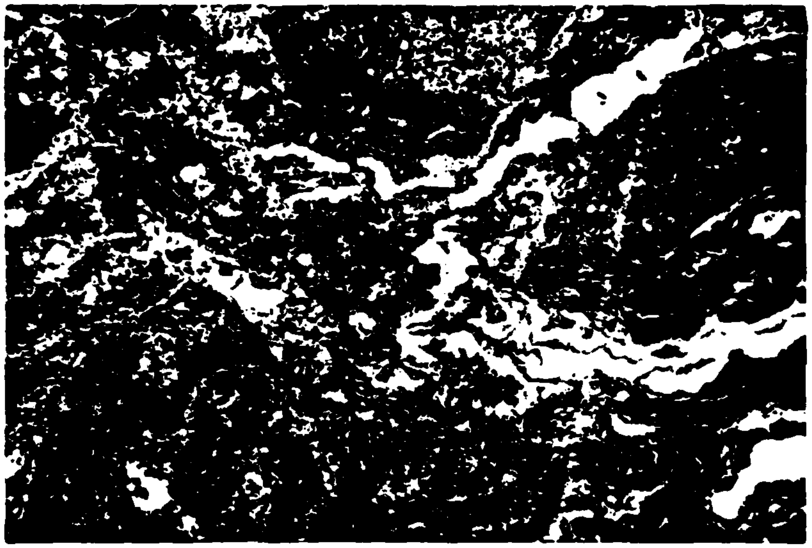


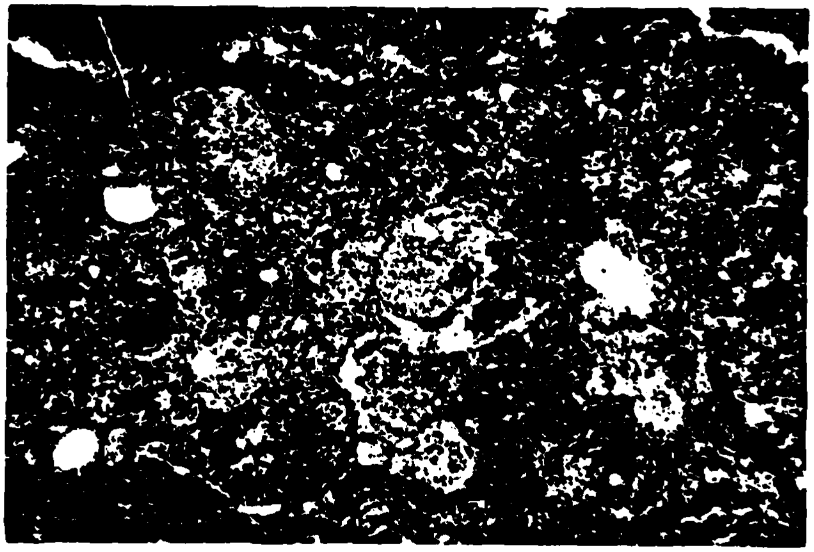
Slide 57-s: Photo # 15

Variations in dense cryptocrystalline calcite of laminar layers (plane light, 2.5 power, 39 total magnification).

Slide 57-s: Photo #16

Pelletoid structure in dense laminar layer (plane light, 2.5 power, 39 total magnification).





Slide 57-pc: Photo #17

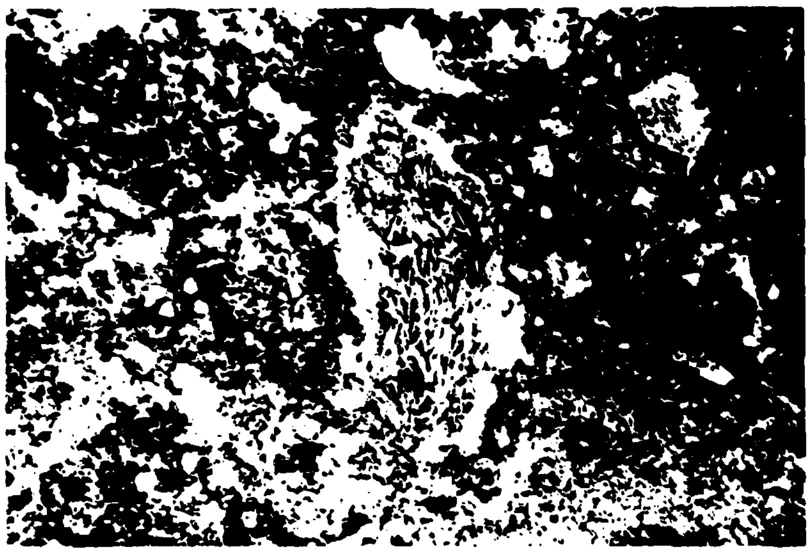
Dense cryptocrystalline calcite layer between two microcrystalline calcite layers (plane light, 2.5 power, 39 total magnification).

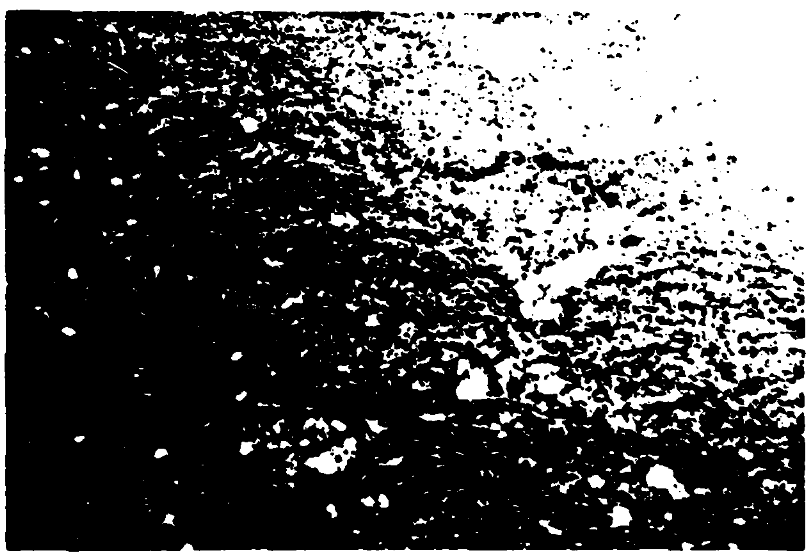
Slide 57-pc: Photo #18

Basalt fragment surrounded by randomly oriented crypto- and microcrystalline calcite with many voids (plane light, 2.5 power, 39 total magnification).

Slide 57-11: Photo #23

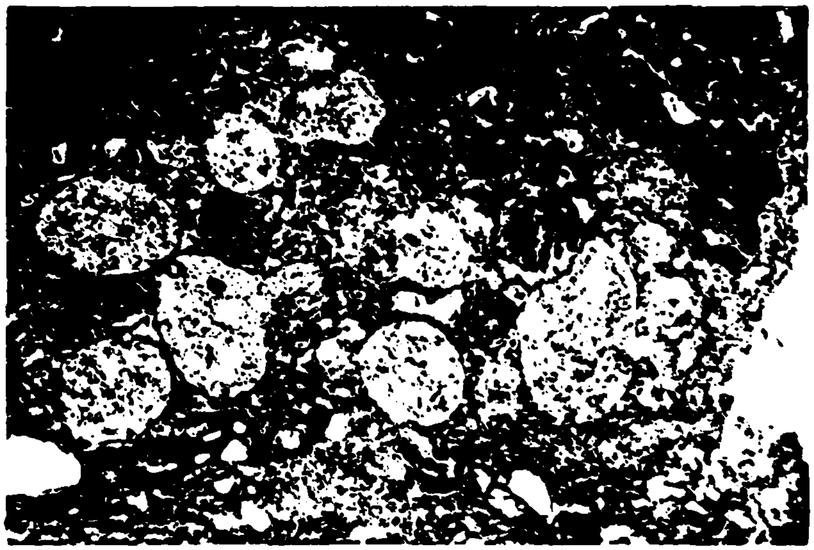
Dense laminar layer with subangular to subrounded quartz grains; biotite and chlorite fragments in center (plane light, 2.5 power, 39 total magnification).





Slide 57-11: Photo #19

Pelletoidal structure in dense laminar layer of cryptocrystalline calcite with voids and subangular quartz fragments (plane light, 2.5 power, 39 total magnification).

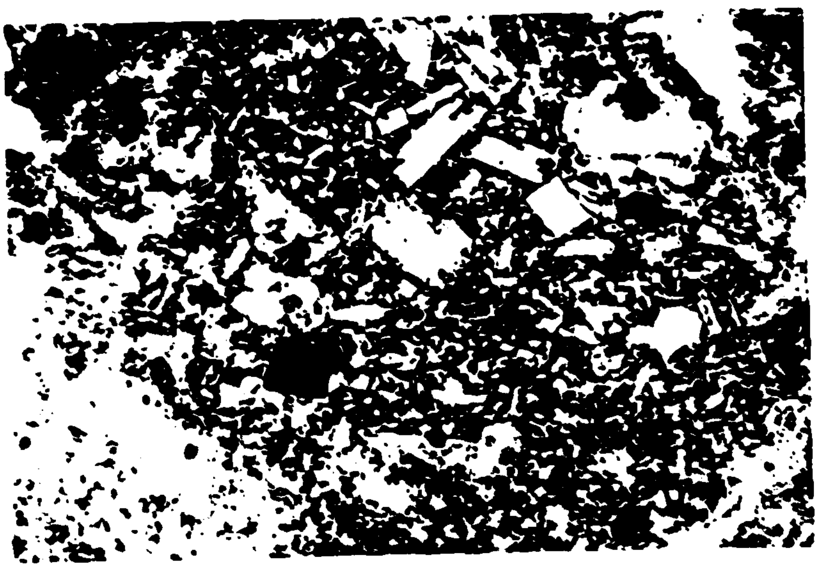


Slide 59-d2: Photo #24

Rounded basalt fragment with oxyhornblende (?) surrounded by microcrystalline calcite (plane light, 2.5 power, 39 total magnification).

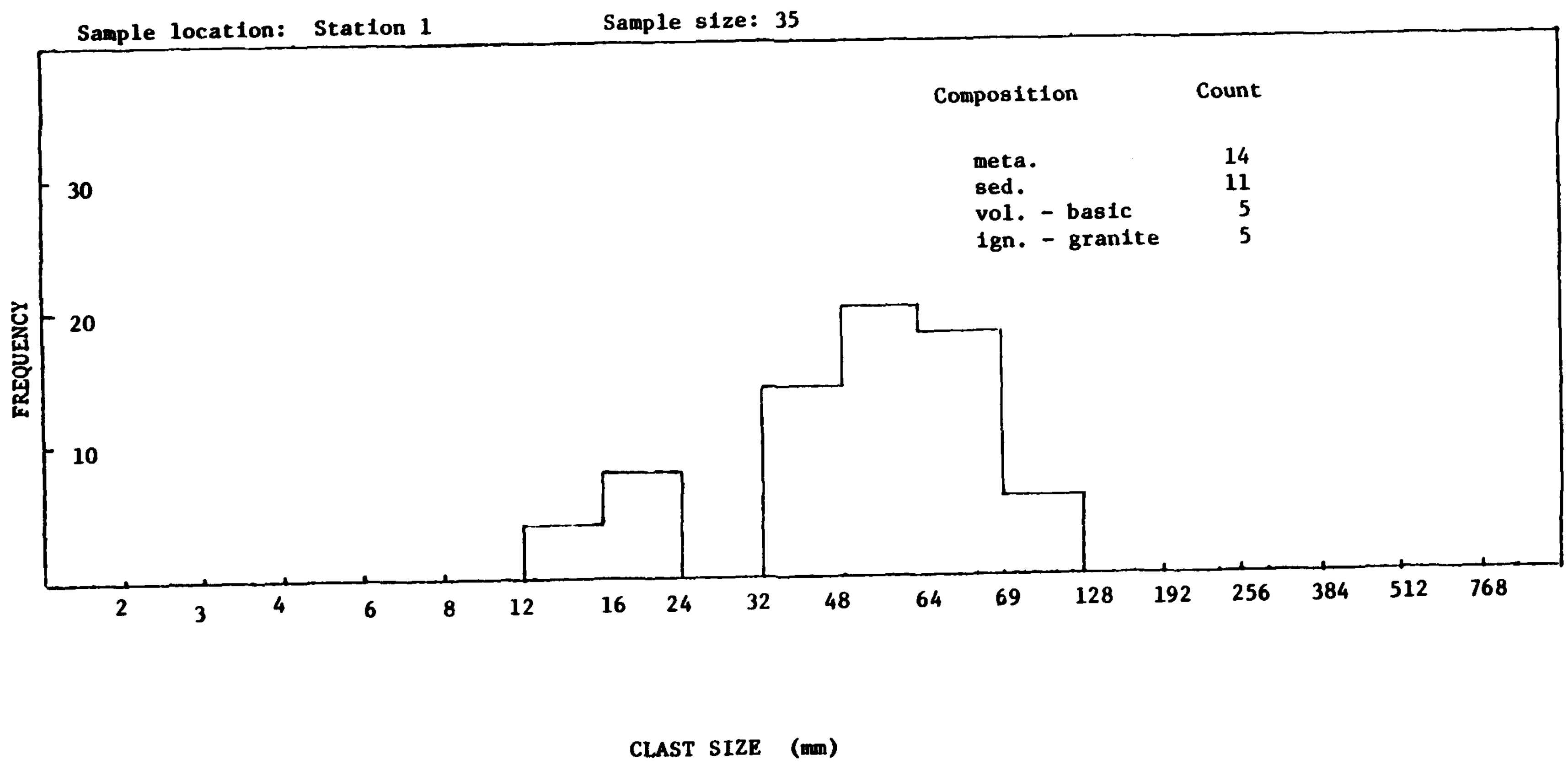
Slide 59-d2: Photo #27

Basalt fragment enclosed by cryptocrystalline calcite (plane light, 2.5 power, 39 total magnification).

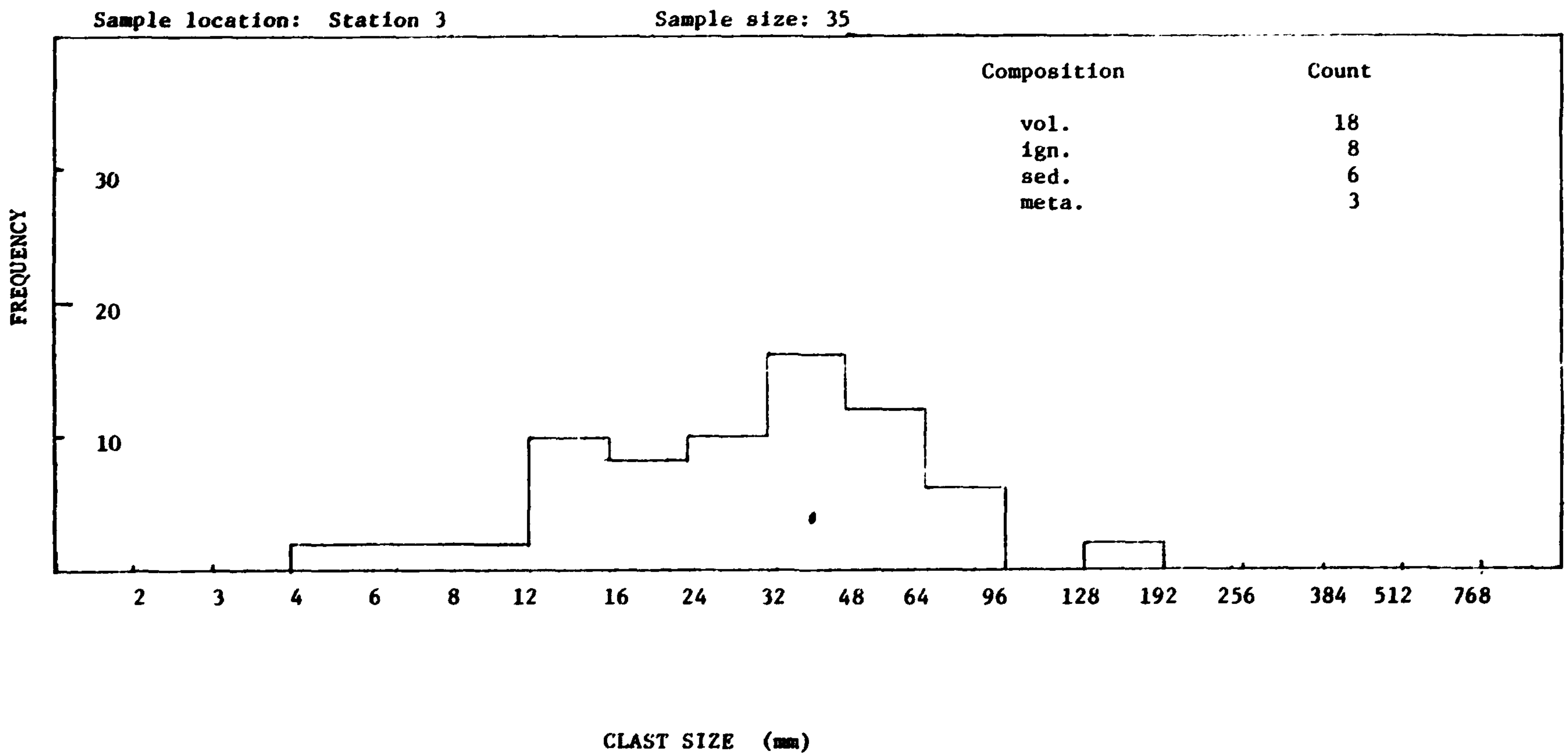


Appendix E

Grain Size Distribution & Percent Parent Material Composition
of Selected Pedogenic Caliche Samples
(see Appendix A for Sample Locations)

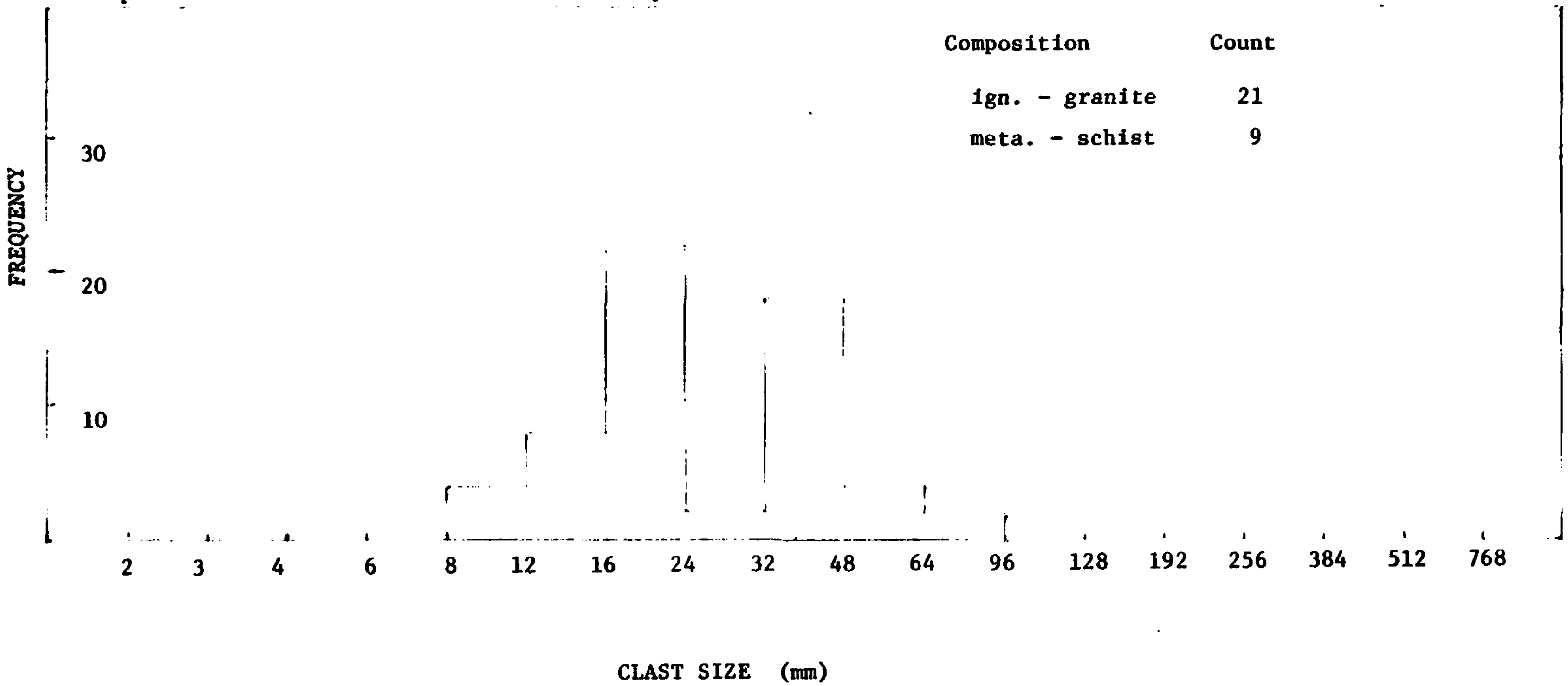


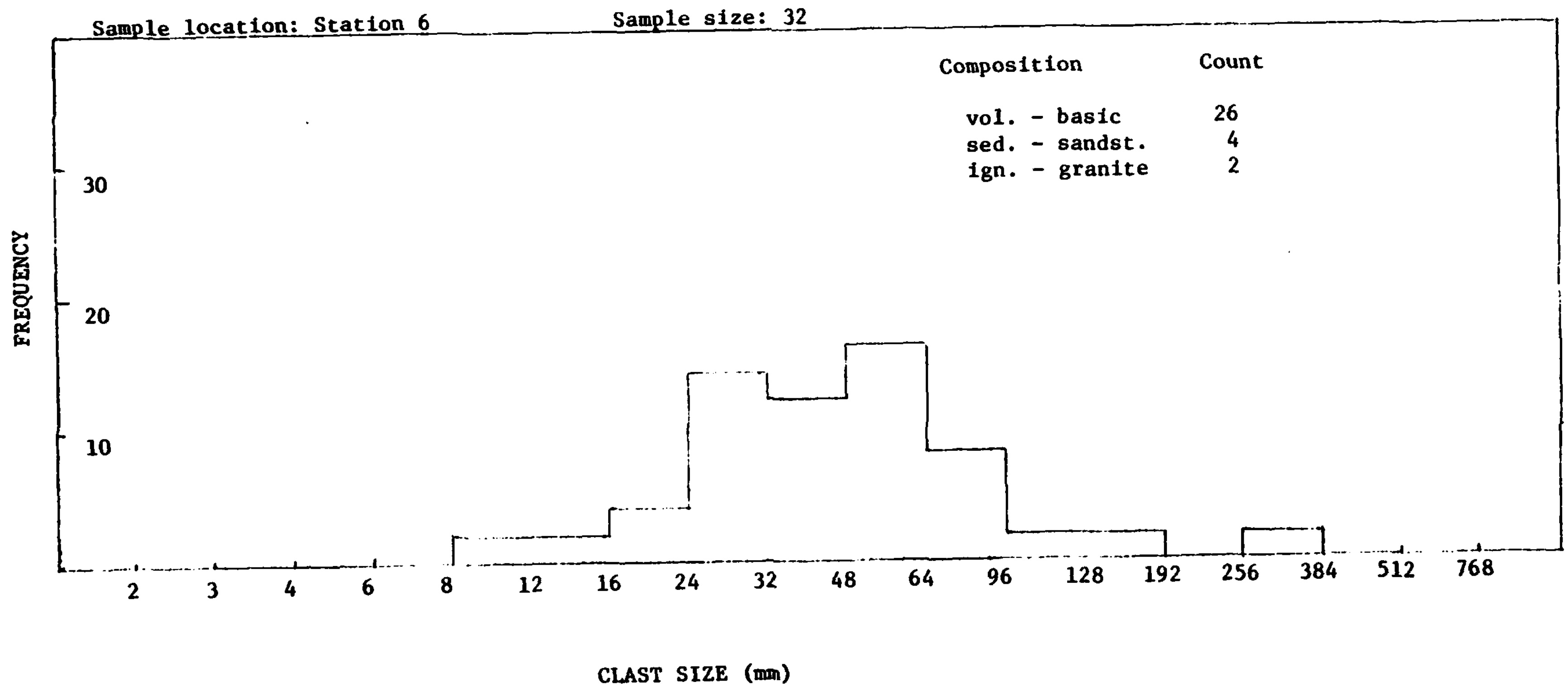
Sample location: Station 1
Sample size: 35
Composition
Count
meta.
14
sed.
11
vol. - basic
5
ign. - granite
5
FREQUENCY
30
20
10
2
3
4
6
8
12
16
24
32
48
64
69
128
192
256
384
512
768
CLAST SIZE (mm)



Sample location: Station 3
Sample size: 35
Composition
Count
vol.
18
ign.
8
sed.
6
meta.
3
FREQUENCY
30
20
10
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768
CLAST SIZE (mm)

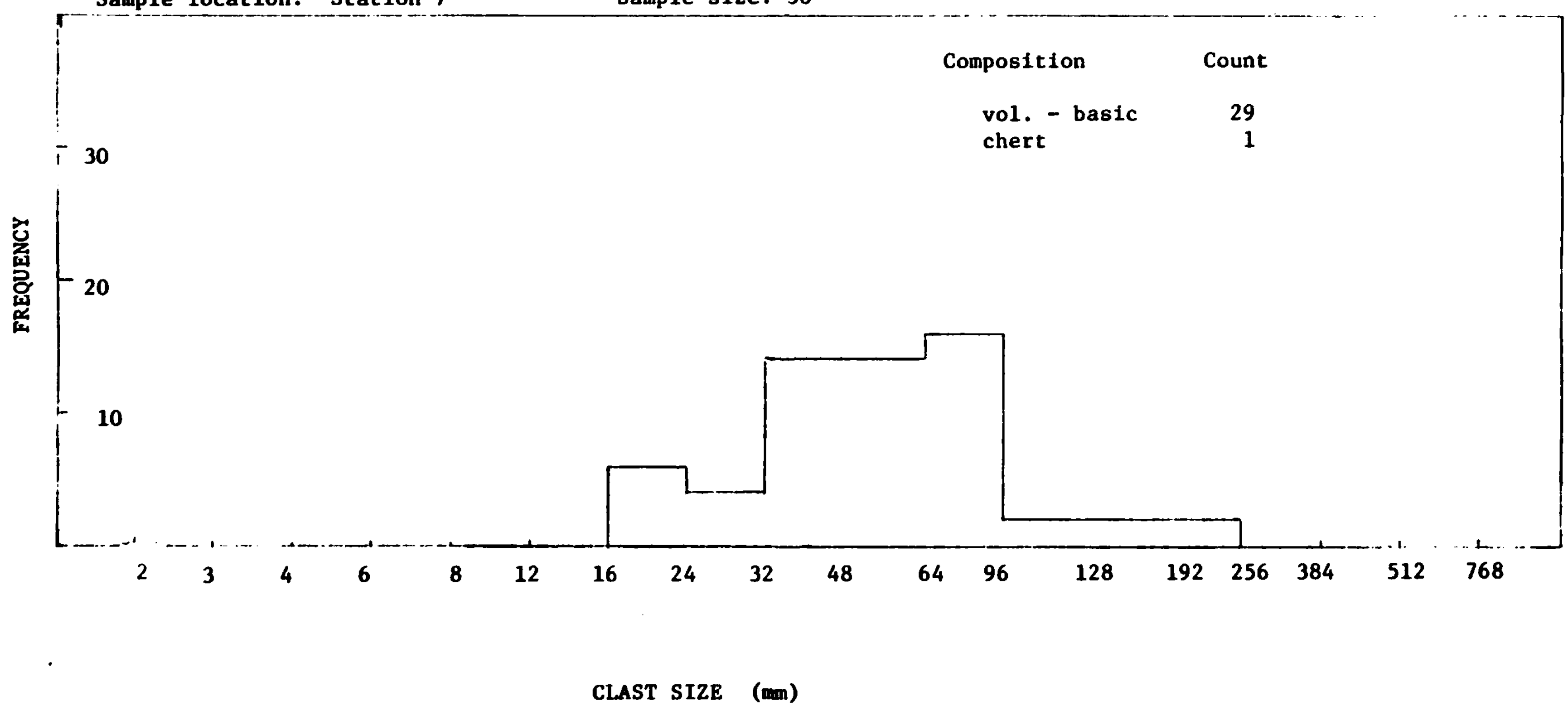
Sample location: Station 4 Sample size: 30

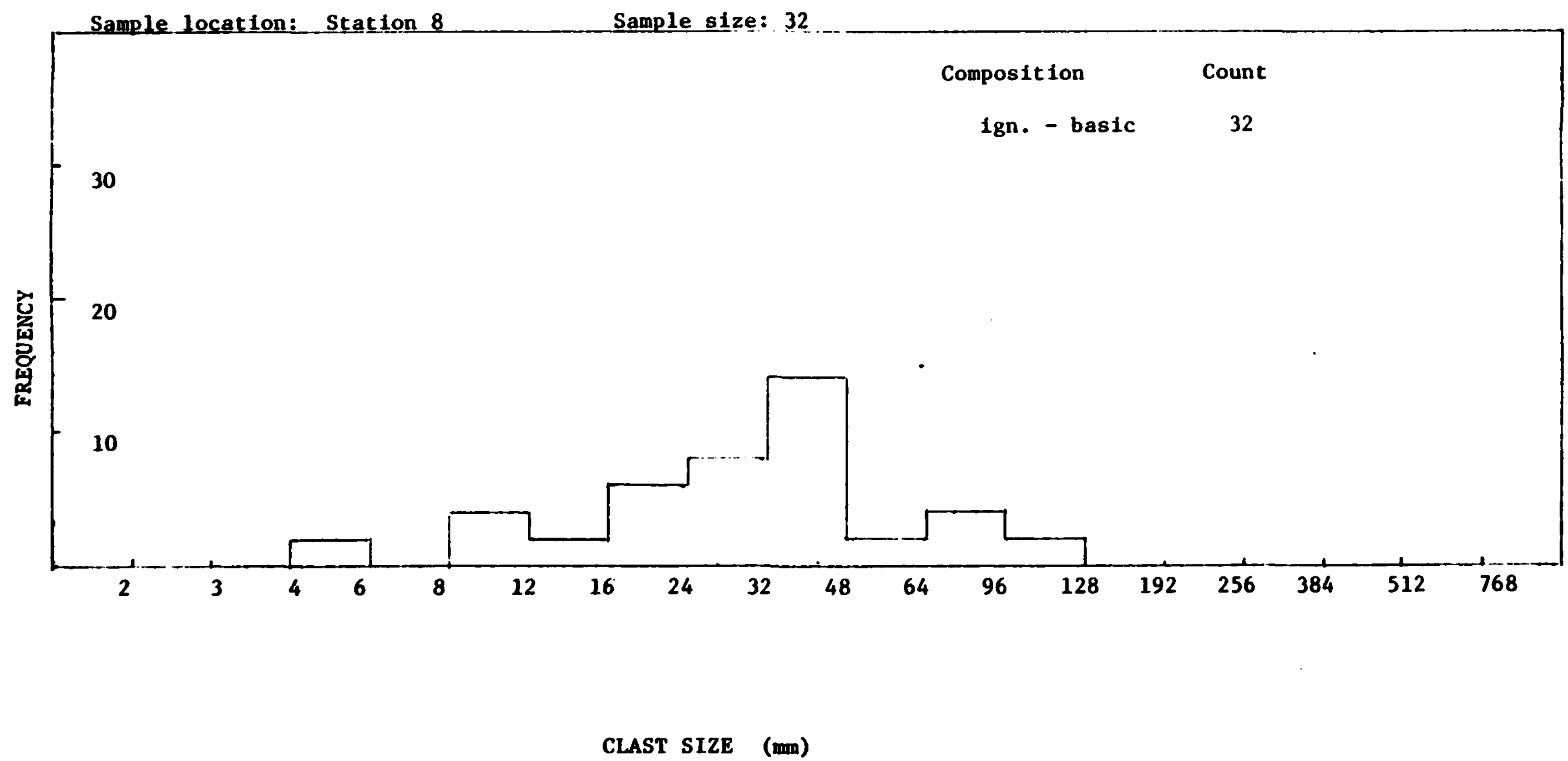


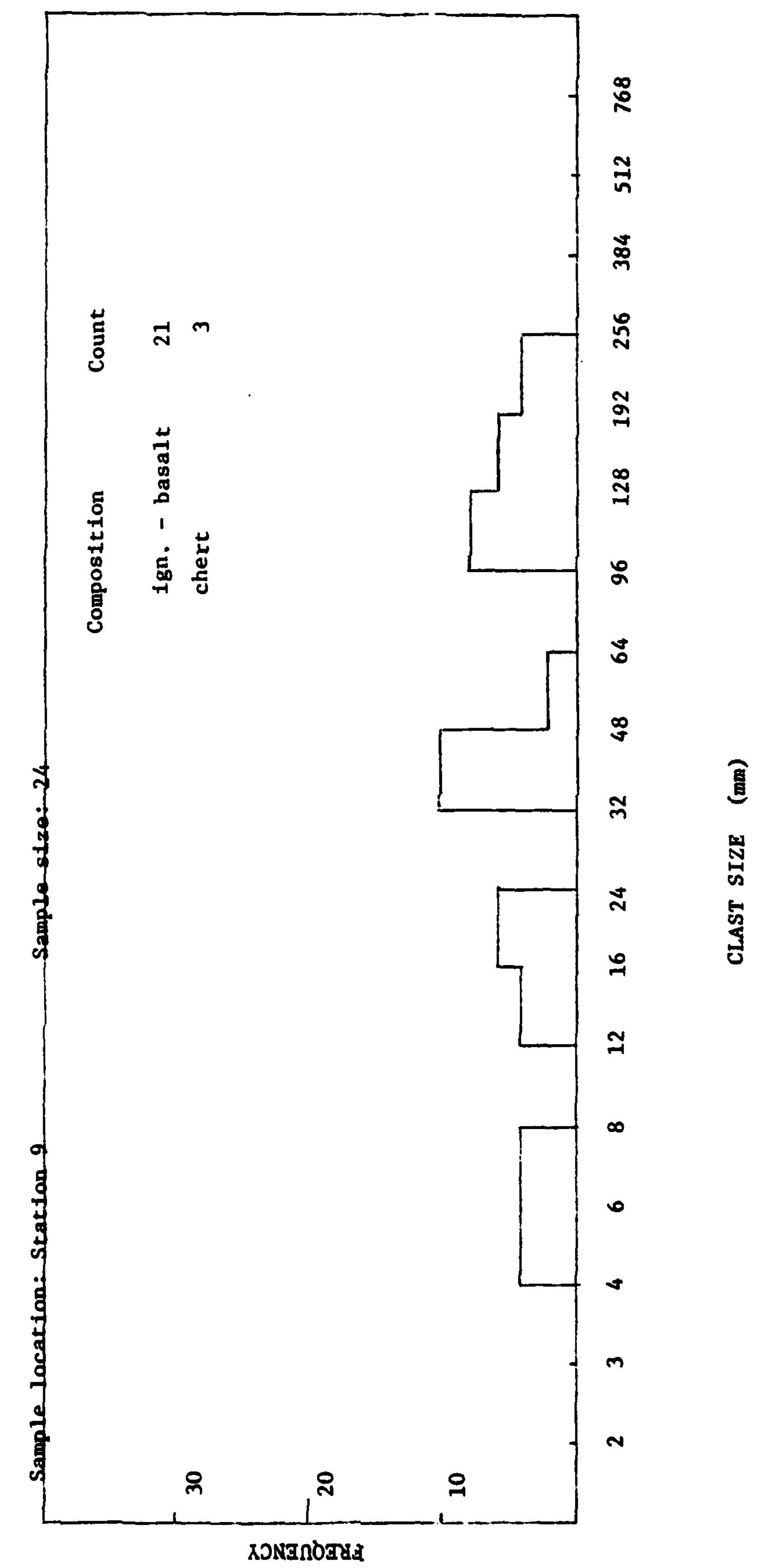


Sample location: Station 6
Sample size: 32
Composition
Count
vol. - basic
26
sed. - sandst.
4
ign. - granite
2
FREQUENCY
30
20
10
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768
CLAST SIZE (mm)

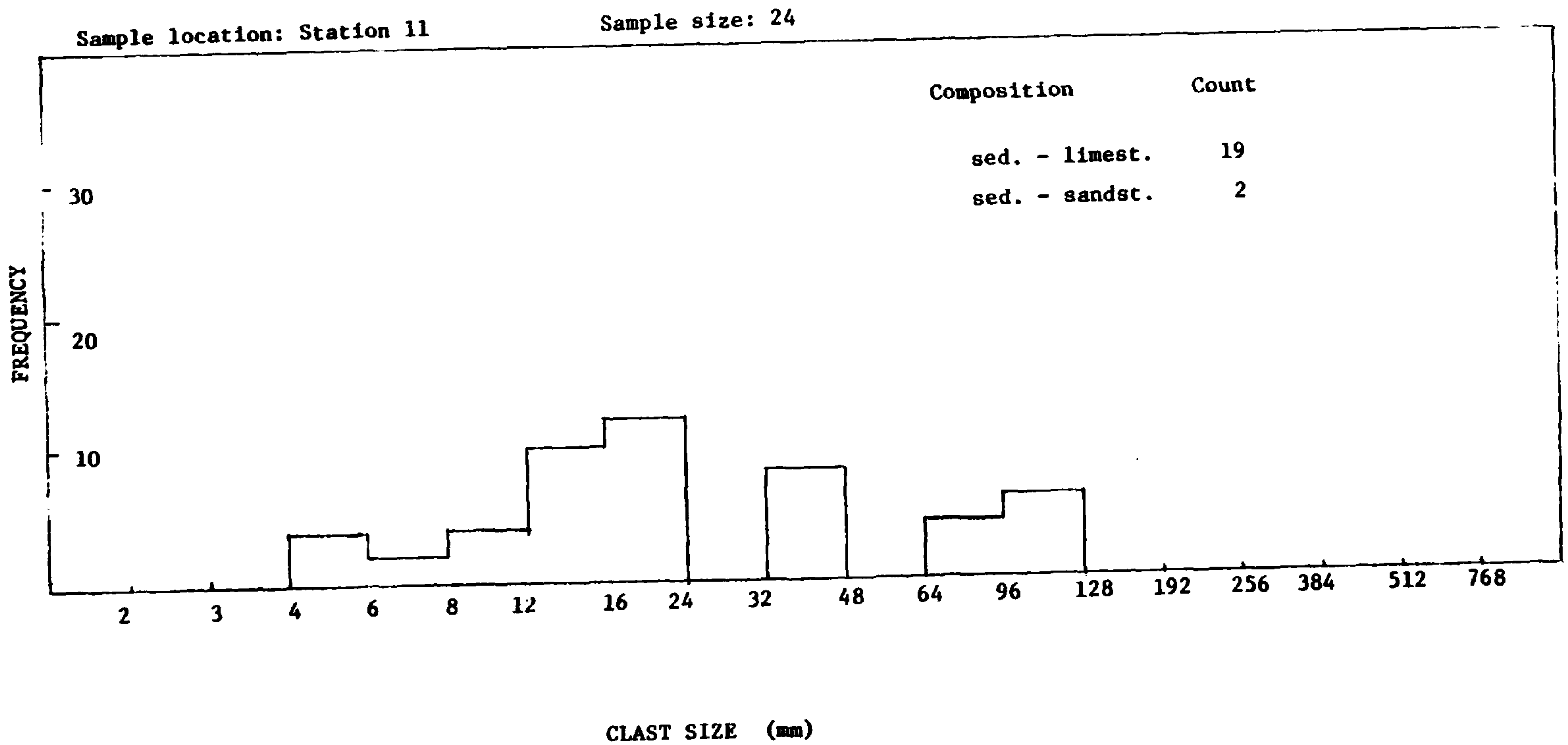
Sample location: Station 7 Sample size: 30

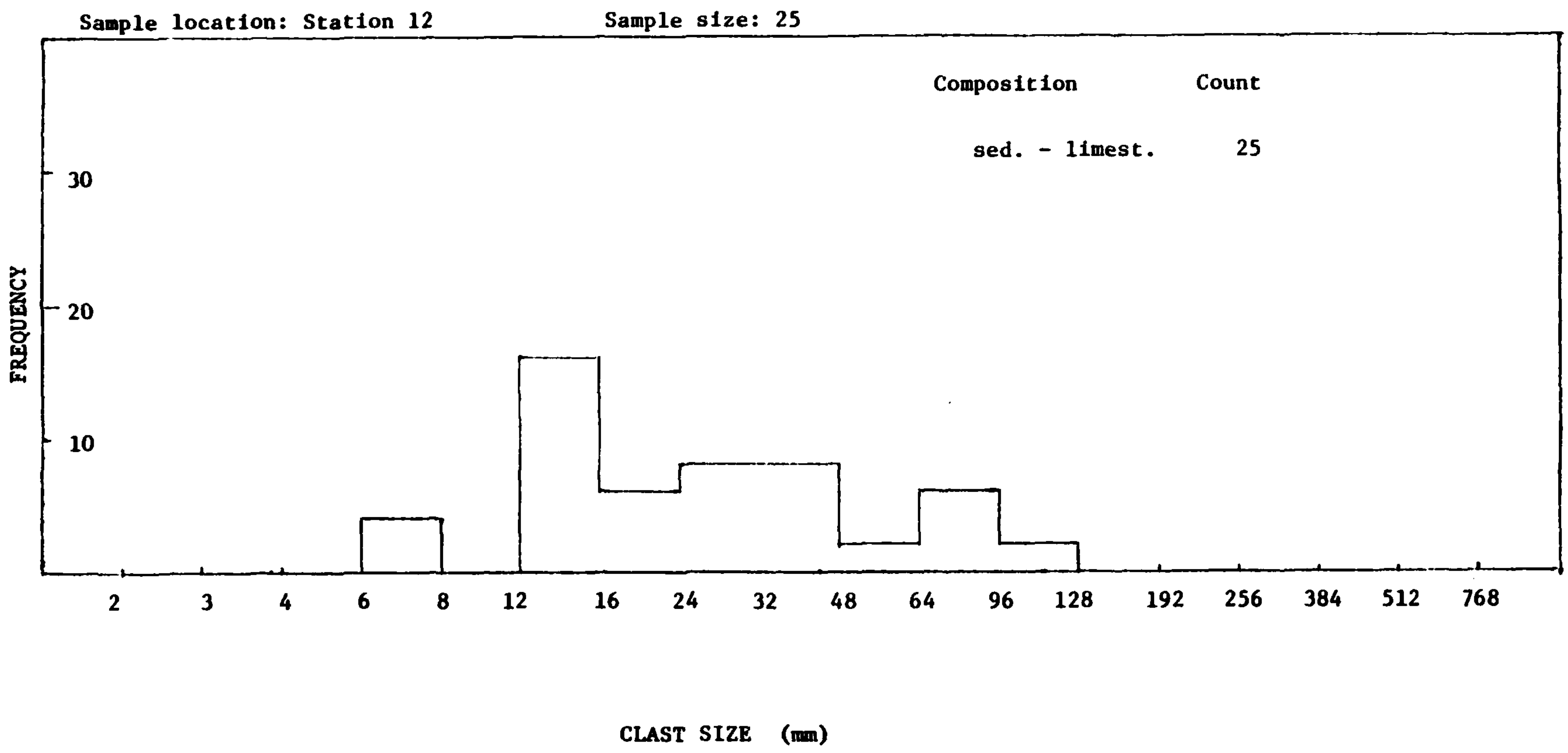



Sample location: Station 8
Sample size: 32
Composition
Count
ign. - basic
32
30
20
10
FREQUENCY
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768
CLAST SIZE (mm)



Sample location: Station 9
Sample size: 24
Composition
Count
ign. - basalt
21
chert
3
FREQUENCY
10
20
30
CLAST SIZE (mm)
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768


Sample location: Station 11
Sample size: 24
Composition
Count
sed. - limest.
19
sed. - sandst.
2
FREQUENCY
30
20
10
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768
CLAST SIZE (mm)


Sample location: Station 12
Sample size: 25
Composition
Count
sed. - limest.
25
FREQUENCY
30
20
10
2
3
4
6
8
12
16
24
32
48
64
96
128
192
256
384
512
768
CLAST SIZE (mm)

## Appendix F

## Techniques for Constructing Maps of Plates IX & X

Details for constructing a slope map (Plate X) are given below: (1) slopes of short segments of a line normal to the contours are determined for each section of a 15-minute topographic map (approximately 2.5 $km^2$) see Figure E-1; (2) the tangent of the slope is calculated, converted to degrees, and plotted at the center of each section shown in the Figure E-1; and (3) isopleths of equal slope are drawn at an interval of $0.25^{\circ}$ for this data. The frequency of the slope angles on the study basin is based on the cumulative measurements of slope angles in each section.

Construction of a drainage texture map (Plate IX) is based on methods devised by Ruhe (1967) and methods developed in the present study. The procedure is as follows:

1. A curve is fitted to the longest contour in each section of the topographic maps shown in the figure, according to those procedures given by Ruhe (1967).

2. Lengths are measured from the fitted curve to the actual contour line parallel to axis of drainage lines. These lengths are totalled for each section, and the result is $L_D$, or the cumulative length of drainage lines produced by erosion.

3. Frequency of the drainage lines for each section, or $N_D$, is multiplied by $L_D$. This number is then calculated for an area of 1 $km^2$, rather than 2.5 $km^2$, and is a measure of the drainage texture.

4. The drainage texture value is plotted in the center of each square in Figure E-1, and isopleths of equal drainage texture are drawn at an interval of 2 km of eroding channel per $km^2$.

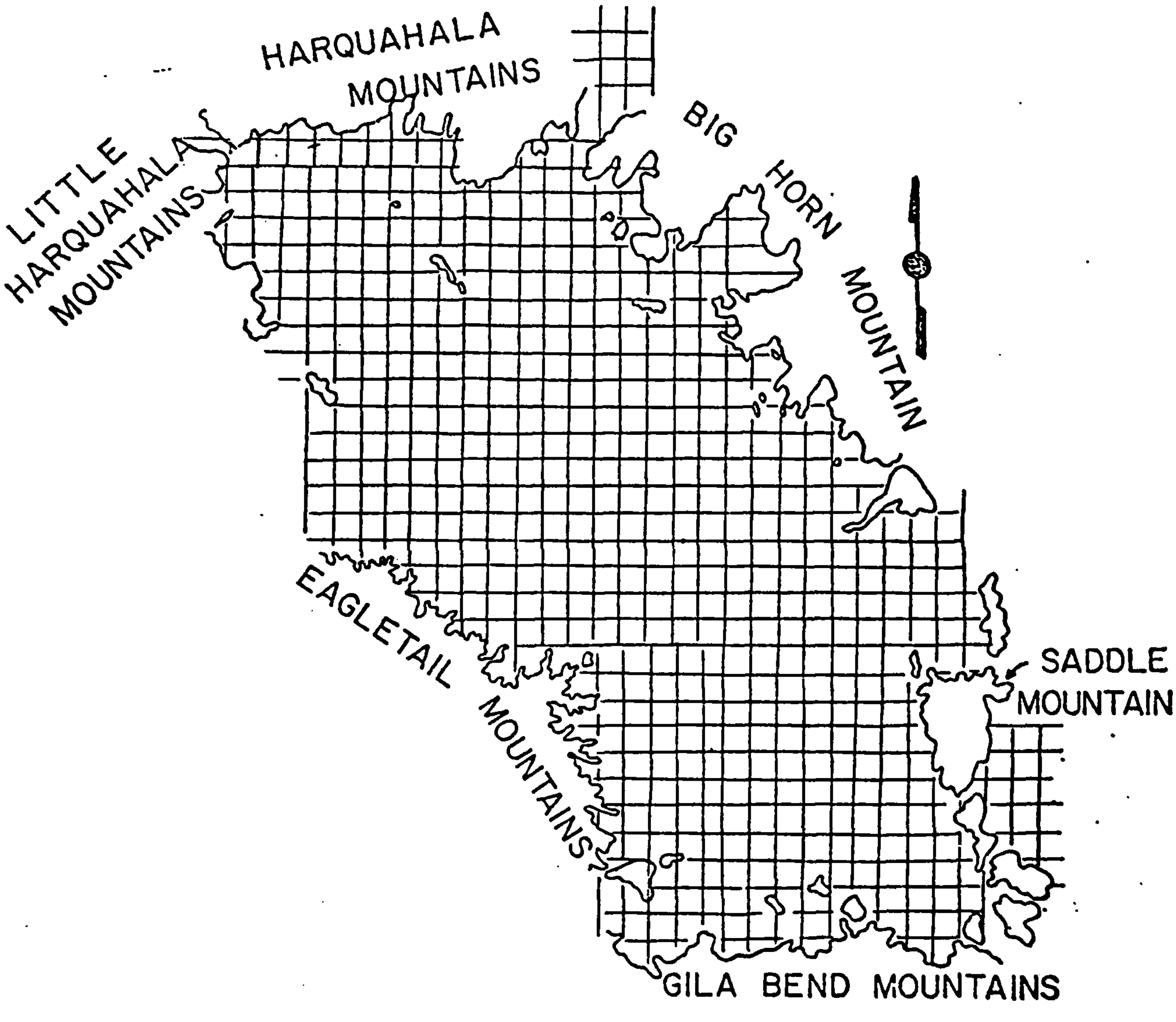



Figure F-1. Grid system used in constructing maps of Plates IX and X.